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Ontario Geological Survey
Open File Report 5716

Stratigraphy and Oil Shale Resource Potential of the Middle Devonian Marcellus Formation, Southwestern Ontario

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ONTARIO GEOLOGICAL SURVEY

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Stratigraphy and Oil Shale Resource Potential of the Middle Devonian Marcellus Formation, Southwestern Ontario

by

M.D. Johnson, P.G. Telford, G. Macauley and J.F. Barker

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V.G. Milne

V.G. Milne, Director
Ontario Geological Survey

FOREWORD

The Hydrocarbon Energy Resources Program consisted of four main components. The Ontario Geological Survey (of the Ministry of Northern Development and Mines) carried out inventories and assessments of the peat, lignite and oil shales resources of the Province. At the same time the Petroleum Resources Section (of the Ministry of Natural Resources) in Southwestern Region reviewed conventional oil and gas resources.

This report is one of the four final reports considering the oil shale resources of the Province. Although largely researched and compiled by O.G.S. staff, the report also includes significant contributions from a diverse group of private consultants and university researchers.

The report describes the oil shale resource potential of the Middle Devonian Marcellus Formation - a largely black shale unit which underlies part of southwestern Ontario and north central Lake Erie. Important new data on the stratigraphy and regional correlation of the formation are also discussed.

V.G. Milne, Director
Ontario Geological Survey

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ABSTRACT

There are several shale formations in southern Ontario which are capable of yielding hydrocarbons when heated. Of these units the Middle Devonian Marcellus Formation is probably the least well known. This study looks at both the stratigraphy and resource potential of this formation. The work is based on a combination of drilling and organic chemical investigations made of the unit. Extensive use was made of down-hole geophysics which provided good corellation between drill holes and aided in the identification of organic rich zones. Results of this study although not conclusive due to the small data set used suggest the following points: the Marcellus Formation is deeply buried below a combination of rock and glacial material, requiring the use of subsurface mining technology for extraction; the organic rich zones in the unit, although they cover an area of several hundred square kilometers are thin (one or two meters) making economic resource extraction unlikley based on present day oil prices. Results from the organic chemical analyses suggest the unit is of moderate hydrocarbon yield relative to the other oil shales present in Ontario.

ONTARIO GEOLOGICAL SURVEY

Open File Report

Stratigraphy and Oil Shale Resource Potential of the Middle Devonian Marcellus Formation Southwestern Ontario

by

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1. INTRODUCTION

1.1 Program Review

Evaluation of the hydrocarbon resource potential of oil shales in Ontario was an activity of the Hydrocarbon Energy Resources Program (HERP). This program was initiated in 1981, with funding supplied by the Ontario Ministry of Treasury and Economics for a five year term ending March 31st 1986.

Development of HERP was in response to an Ontario government decision, made in the Fall of 1979, that the province should endeavour to raise its energy self-sufficiency from the then current level of 23%. A target of 37.5% energy self-sufficiency by 1995 was established. As part of the 1979 decision, the Ontario Geological Survey was given the mandate to carry out an inventory of the province's hydrocarbon energy resources and to determine the contribution that they could make to greater energy self-sufficiency.

HERP consisted of four major components corresponding to the four types of hydrocarbon deposits known to be present in the province. The Ontario Geological Survey has been responsible for conducting inventories and evaluations of peat, lignite, and oil shale resources. The Petroleum Resources Section (Ontario Ministry of Natural Resources) in London was assigned to review the province's reserves and potential resources of conventional oil and natural gas. These wide-ranging, multi-facetted activities were carried out through a combination of provincial government surveys, university-based research projects, and studies contracted to private geological and engineering consulting firms. In addition, close liaison was maintained with relevant departments of the federal government, and other provincial governments, to facilitate vital information exchange and co-operative ventures. Overall management and co-ordination of the program and dissemination of results were the responsibility of the Ontario Geological Survey.

This report is one of four final reports dealing with the component of HERP that has become known as the Oil Shale Assessment Project. The principal objective of this project was to determine the hydrocarbon resource potential of the oil shales in Ontario. This was the most comprehensive study of specific oil shale resources conducted to date in Canada.

1.2 Oil Shale Concepts and Definitions

An "oil shale" is not necessarily a shale and it does not contain oil in the same sense as conventional oil deposits. Because usage of the term arose long before there was understanding of the geological nature of the deposits in question, or of the character of the organic components in the rocks, "oil shale" has been one of the most loosely defined geological terms (Macauley, 1984). Clarification of this situation is provided by Macauley (1984) and Macauley et al. (1985). Their definition of oil shale, which has been used in the Ontario Geological Survey investigations, is as follows:

> Oil shale is a fine grained, sedimentary rock, containing indigenous organic matter that is mainly insoluble in ordinary petroleum solvents, and from which significant amounts of shale oil can be extracted by pyrolysis (i.e. heating in a retort).

Several of the terms in this definition require further explanation. For example, the phrase "significant amounts" is somewhat open-ended but justification of its use is described by Macauley et al. (1985, p.2) as follows.

"The temperature of pyrolysis [of oil shales] seldom exceeds 500° to 600°C as, above these temperatures, additional yield of shale oil is low, and breakdown occurs for some of the inorganic rock constituents, especially dolomite. The energy necessary to raise the rock temperature to 500°C is approximately 150 calories/gram of rock. The heat value of the indigenous organic material is generally 10,000 calories/gram; therefore 2.5% by weight is the minimum organic content at which the amount of energy recovered as shale oil could theoretically balance the input energy. This value, then, becomes the minimum organic content needed to define an oil shale, but does not allow for other energy-equivalent input (mining, transportation, etc.). U.S. literature often quotes 10 US gallons/ton (42 litres/ tonne) as a minimum shale oil yield for economic consideration, but this is an arbitrary value."

The indigenous organic matter of oil shale is mainly kerogen. This is a solid organic material, insoluble in normal organic solvents, which on heating and decomposition produces shale oil. The nature of kerogen, as determined by geochemical analysis and petrological examination, is commonly used as the basis for oil shale classification schemes (e.g. Macauley *et al*. 1985).

Tissot and Welte (1978) divided kerogen into three types based on atomic hydrogen/carbon ratios. Type I (H/C >1.4) is derived from algae and is commonly a non-marine deposit; Type II (H/C <1.4-1.2) is derived from phytoplankton and is marine; Type III (H/C <1.0) is derived from higher land plants. Types I and II can produce oil shale while Type III produces coal. Despite these apparently simple subdivisions, kerogens can display considerable variation from deposit to deposit and even between different stratigraphic levels and geographic zones in a single deposit.

Shale oil is the product of pyrolysis of oil shale and should not be confused with crude oil (petroleum) obtained from conventional sources. The character of shale oil depends on the type and composition of the kerogen from which it is derived but it will always be an undersaturated (i.e. hydrogen-depleted) hydrocarbon. Therefore, shale oil will always require further refining (i.e. hydrogenation) to produce a petroleum equivalent to that from conventional oil reservoirs (Macauley, 1984).

There is some confusion in the literature with regard to descriptive terms commonly applied to shales and other rocks with an organic constituent. The terms bituminous, petroliferous, kerogenous, and carbonaceous are often used incorrectly. The following guidelines should be noted.

- Petroliferous rocks are those containing a liquid petroleum phase
- Bituminous rocks contain soluble solid hydrocarbon.
- Kerogenous rocks contain insoluble organic material (i.e. kerogen).
- Carbonaceous rocks contain organic carbon and minimal hydrogen content denoting the presence of higher plant remains.

1.3 Oil Shale Assessment Project

According to the definitions described above, four Paleozoic stratigraphic units in Ontario may be classified as oil shales and have been investigated as part of the Oil Shale Assessment Project (Table 1). The initial phase of the project (1981-82) included an intensive study of the Upper Ordovician rock unit commonly termed the Collingwood shale but now formally defined as the Collingwood Member of the Lindsay Formation (Russell and Telford 1983). In 1982, this work was joined by similar investigations of the Devonian Marcellus and Kettle Point Formations of southwestern Ontario. Then, in 1984, the project was expanded to involve detailed stratigraphic study and assessment of the Upper Devonian Long Rapids Formation in the Moose River Basin (James Bay Lowland).

The data gathering activities for the three southern Ontario oil shales followed a similar pattern but geographical and logistical constraints necessitated a somewhat different approach to evaluation of the Long Rapids Formation (Russell and Telford, 1984b). Data for the southern Ontario units were obtained mainly through outcrop examination, considerable diamond drilling, and organic geochemical analysis of selected samples. In addition, specialized sedimentological and paleontological studies of key stratigraphic intervals were undertaken (e.g. Harris, 1985; Tuffnell and Ludvigsen, 1984) and the inorganic geochemistry and physical properties of particular units were also considered (e.g. Delitala, 1984; Dusseault and Loftsson 1985).

Outcrops of the southern Ontario oil shales are very meagre; the Marcellus Formation is completely buried by Pleistocene glacial and lacustrine sediments. Also, where present, outcrops of the Collingwood Member and Kettle Point Formation are of only limited stratigraphic extent. Complete sections through these units are nowhere exposed and upper and lower contacts rarely appear in outcrop. Therefore,

FORMATION	AGE	LOCATION
Collingwood Member (Lindsay Formation)	Upper Ordovician	Southcentral Ontario, Manitoulin Island and St. Joseph Islands.
Marcellus	Middle Devonian	Southwestern Ontario
Kettle Point	Upper Devonian	Southwestern Ontario
Long Rapids	Upper Devonian	James Bay Lowland

TABLE 1. Paleozoic Oil Shales of Ontario investigated by the Ontario Geological Survey.

considerable efforts were made to obtain subsurface data to supplement the generally inadequate surface information.

Over 60 shallow drillholes (aimed at specific stratigraphic intervals) and 12 deep drillholes (extending from surface to the Precambrian basement) have been completed in southern Ontario and on Manitoulin, Cockburn, and St. Joseph Islands in northern Lake Huron. All holes were fully cored and geophysically logged. Over 9,000 metres of core has been generated. Most of the drilling and geophysical data has already been released in a series of Ontario Geological Survey Open File Reports (Johnson, 1983, 1985; Johnson _et_ _al_. 1983a, 1983b, 1985).

Approximately 2,000 core samples were selected from the oil shale intervals for hydrocarbon analysis. They were analyzed for total organic carbon (TOC) by rapid pyrolysis methods developed at the University of Waterloo under the direction of Dr. J.F. Barker (see Appendix 1). A number of the samples were also subjected to Fischer Assays, the traditional method of oil yield determination for oil shales, to establish correlation between this and the rapid pyrolysis method (Stromquist _et_ _al_. 1984).

Samples from the Collingwood Member and Kettle Point Formation were supplied to the Institute of Sedimentary and Petroleum Geology (ISPG) in Calgary for appraisal by the Rock-Eval pyrolysis method (Snowdon, 1984). Several samples of the Collingwood Member were given to CANMET (Ottawa) for testing in the hydrogen retorting system under development by the New Brunswick Research and Productivity Council. Several samples from the Kettle Point Formation were also analyzed by the Institute of Gas Technology (IGT) in Chicago using their patented Hytort method.

The prodigious body of data generated by the outcrop examinations, drilling, and laboratory activities, together with the results of the sedimentological, paleontological, petrological and other studies are being assembled and synthesized in a series of assessment reports on the four rock units (Table 1) under investigation.

This report describes the stratigraphy, distribution, and hydrocarbon resource potential of the Marcellus Formation.

1.4 Project Participants and Acknowledgments

In addition to the two main OGS researchers involved in this project (M.D. Johnson and P.G. Telford), significant contributions were also made by the following people. Dr. J.F. Barker (University of Waterloo) carried out organic geochemical analyses and prepared Appendix I. George Macauley (Calgary) assisted in preparation of the resource evaluation (section 5). Additional Rock-Eval analytical data was provided by Lloyd Snowdon (at the Institute of Sedimentary and Petroleum Geology- Calgary).

Basis for much of the work has been the drill holes through the Marcellus Formation. The shallow hole coring

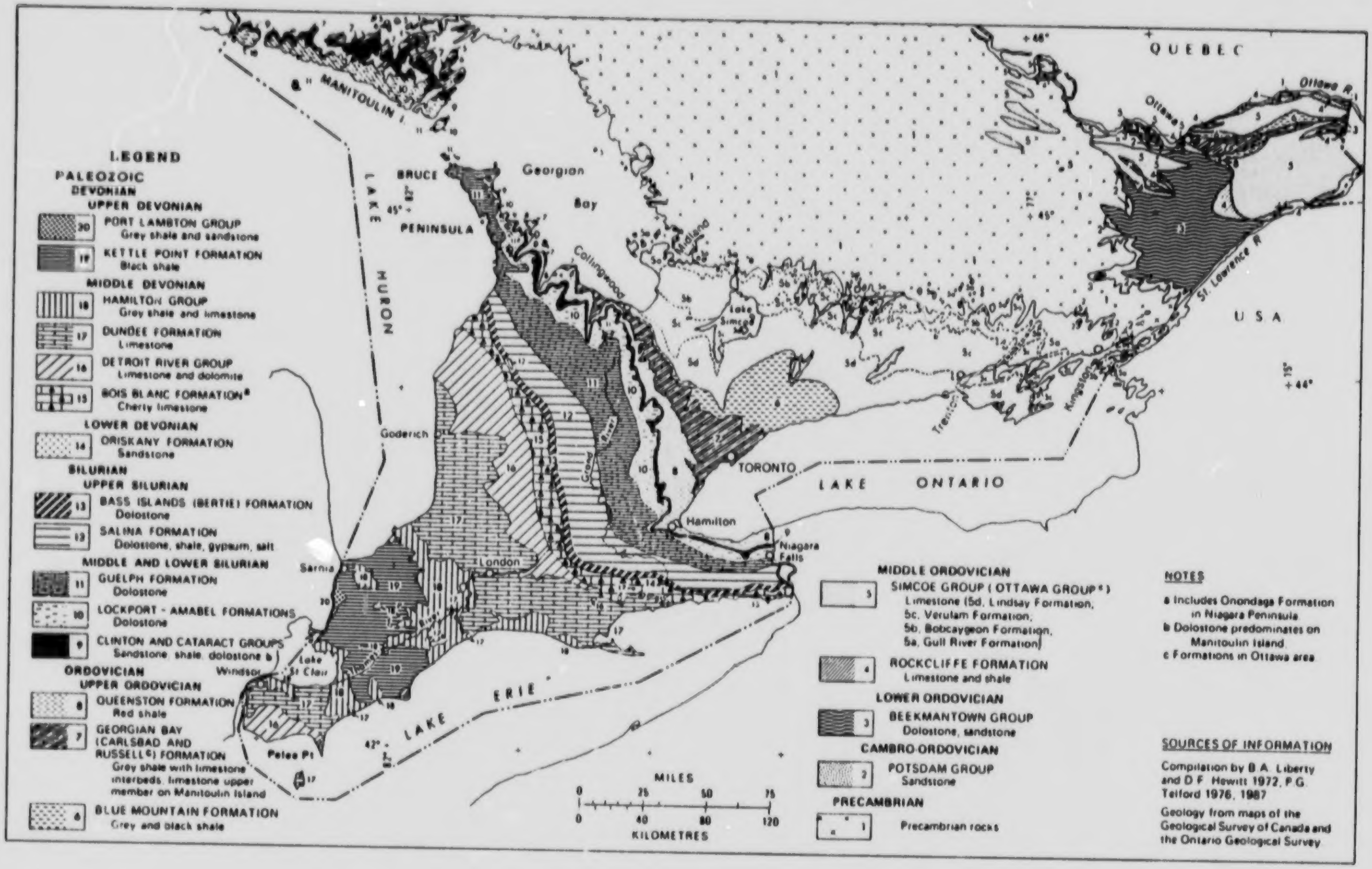

LEGEND
PALEOZOIC
DEVONIAN
UPPER DEVONIAN
20 PORT LAMBTON GROUP Grey shale and sandstone
19 KETTLE POINT FORMATION Black shale
MIDDLE DEVONIAN
18 HAMILTON GROUP Grey shale and limestone
17 DUNDEE FORMATION Limestone
16 DETROIT RIVER GROUP Limestone and dolomite
15 BOIS BLANC FORMATION a Cherty limestone
LOWER DEVONIAN
14 ORISKANY FORMATION Sandstone
SILURIAN
UPPER SILURIAN
13 BASS ISLANDS (BERTIE) FORMATION Dolostone
12 SALINA FORMATION Dolostone, shale, gypsum, salt
MIDDLE AND LOWER SILURIAN
11 GUELPH FORMATION Dolostone
10 LOCKPORT - AMABEL FORMATIONS Dolostone
9 CLINTON AND CATARACT GROUPS Sandstone, shale, dolostone b
ORDOVICIAN
UPPER ORDOVICIAN
8 QUEENSTON FORMATION Red shale
7 GEORGIAN BAY (CARLSBAD AND RUSSELL c) FORMATION Grey shale with limestone interbeds, limestone upper member on Manitoulin Island
6 BLUE MOUNTAIN FORMATION Grey and black shale
MIDDLE ORDOVICIAN
5 SIMCOE GROUP (OTTAWA GROUP c) Limestone (5d, Lindsay Formation, 5c, Verulam Formation, 5b, Bobcaygeon Formation, 5a, Gull River Formation)
4 ROCKCLIFFE FORMATION Limestone and shale
LOWER ORDOVICIAN
3 BEEKMANTOWN GROUP Dolostone, sandstone
CAMBRO-ORDOVICIAN
2 POTSDAM GROUP Sandstone
PRECAMBRIAN
1 Precambrian rocks
NOTES
a Includes Onondaga Formation in Niagara Peninsula
b Dolostone predominates on Manitoulin Island
c Formations in Ottawa area
SOURCES OF INFORMATION
Compilation by B.A. Liberty and D.F. Hewitt 1972, P.G. Telford 1976, 1987
Geology from maps of the Geological Survey of Canada and the Ontario Geological Survey
QUEBEC
U.S.A.
MANITOULIN I.
BRUCE PENINSULA
Georgian Bay
LAKE HURON
LAKE ONTARIO
LAKE ERIE
Ottawa R.
Ottawa
St. Lawrence R.
Kingston
Trenton
Midland
Collingwood
Lake Simcoe
TORONTO
Hamilton
Niagara Falls
Grand River
Goderich
London
Sarnia
Lake St Clair
Windsor
Pelee Pt
46°
45°
44°
42°
MILES
0 25 50 75
0 40 80 120
KILOMETRES

Fig. 1. Paleozoic Geology of Southern Ontario.

program was undertaken during 1982 by Site Investigation Services Ltd. (Peterborough) who completed the holes only with great difficulty (due to boulder beds and sand lenses in the overburden). The Port Stanley OGS-82-3 deep core, was drilled by Canadian Mine Services Ltd (Bramalea). Geophysical logging of the holes was by British Plaster Board (B.P.B.) Ltd. (Calgary) and Schlumberger Ltd. (contracted from its Chatham office).

Assisting in the early interpretation of the Marcellus was K. Lee Bradshaw, and the integrated drillhole logs and map were produced subsequently by George Flach and Karen Yonge (all from the O.G.S.).

Data for the inorganic geochemistry section was provided by G. Brown (unpublished B.Sc. thesis from the University of Western Ontario).

Preliminary drafts of this manuscript were reviewed by Rainer Wolf and D.K. Armstrong (both OGS).

2. PALEOZOIC GEOLOGY OF SOUTHERN ONTARIO

2.1 Structural and Paleogeographic Setting

Paleozoic strata form the bedrock of two discrete parts of southern Ontario, each of which has its own distinctive structural style and differing paleogeographic histories. In southeastern Ontario, east of the Frontenac Axis, Lower to Middle Ordovician sandstones, shales, and carbonate rocks underlie the physiographic region known as the Ottawa-St. Lawrence Lowland (Fig. 1). West of the Frontenac Axis and south of the Precambrian Shield, in southcentral and southwestern Ontario, Upper Cambrian to Upper Devonian strata underlie an area of approximately 70,000 km^2 forming part of the Great Lakes-St. Lawrence Lowland. Manitoulin, Cockburn, and St. Joseph Islands in northern Lake Huron, which are underlain by Ordovician and Silurian strata, are also included in this geological-physiographic unit (Fig. 1).

Ottawa-St. Lawrence Lowland. The Ordovician sediments of the Ottawa-St. Lawrence Lowland were deposited in a relatively narrow embayment extending northwestward from the northern Appalachian Basin. Unlike the strongly folded, lithologically diverse strata of the Appalachian Basin which were formed in a tectonically active continental margin environment, the strata in the Ottawa-St. Lawrence Lowland are generally flat-lying and of comparatively uniform composition. They were formed in a stable shallow shelf environment mainly unaffected by Paleozoic orogenic episodes. However, during the Late Mesozoic, tectonic activity associated with the opening of the Atlantic Ocean produced block faulting along a structure termed the Ottawa-Bonnechere Graben. The trend of this feature essentially paralleled the original depositional embayment although the block faulting of the Ordovician strata was most severe in the northern part of the Ottawa-St. Lawrence Lowland, along the present valley of the Ottawa River.

Recent mapping by the Ontario Geological Survey in this area has provided a clear picture of the stratigraphic sequence and structural patterns (Williams and Wolf, 1982; Williams and Rae, 1983). A thickness of up to 1130 m of Ordovician strata is present. Steeply dipping normal faults and fault zones are common and some have up to 900 m of vertical displacement. Bedding is normally close to horizontal and steep dips only occur in close proximity to faults and within fault zones.

Limited attention was given to the oil shale resource potential of this region. The Eastview Member (Lindsay Formation) and Billings Formation are Upper Ordovician black shales which outcrop and subcrop beneath surficial deposits in several small areas east of Ottawa (Williams et al. 1984). Initially the Eastview Member was of particular interest to the Oil Shale Assessment Project as the unit is correlative with and lithologically similar to the Collingwood Member

(Lindsay Formation) of southwestern Ontario (Russell and Telford, 1983) which is a confirmed oil shale of significant resource potential (Macauley 1984). However, preliminary organic geochemical analyses of core samples from the Eastview and Billings were discouraging. The apparently rich organic content of the shales was over-mature and potential oil yields correspondingly low (Johnson 1982). This was probably the result of the intense Late Mesozoic tectonism in the region.

Great Lakes-St. Lawrence Lowland. The Upper Cambrian to Upper Devonian stratigraphic succession of southcentral and southwestern Ontario contains a variety of platform deposits formed in a shallow epi-continental sea. Superficially the geology appears to be simple - apparently flat-lying carbonate, clastic and evaporitic units displaying little evidence of severe structural disturbances. However, deposition of these units took place in and around three major paleogeographic elements (Fig. 2):

(a) Appalachian Basin, an elongate sedimentary basin extending into the Niagara Peninsula and beneath Lake Erie.

(b) Algonquin Arch, a broad basement ridge forming the spine of the southwestern Ontario peninsula.

(c) Michigan Basin, a roughly circular sedimentary basin whose eastern rim approximates the axis of the Algonquin Arch.

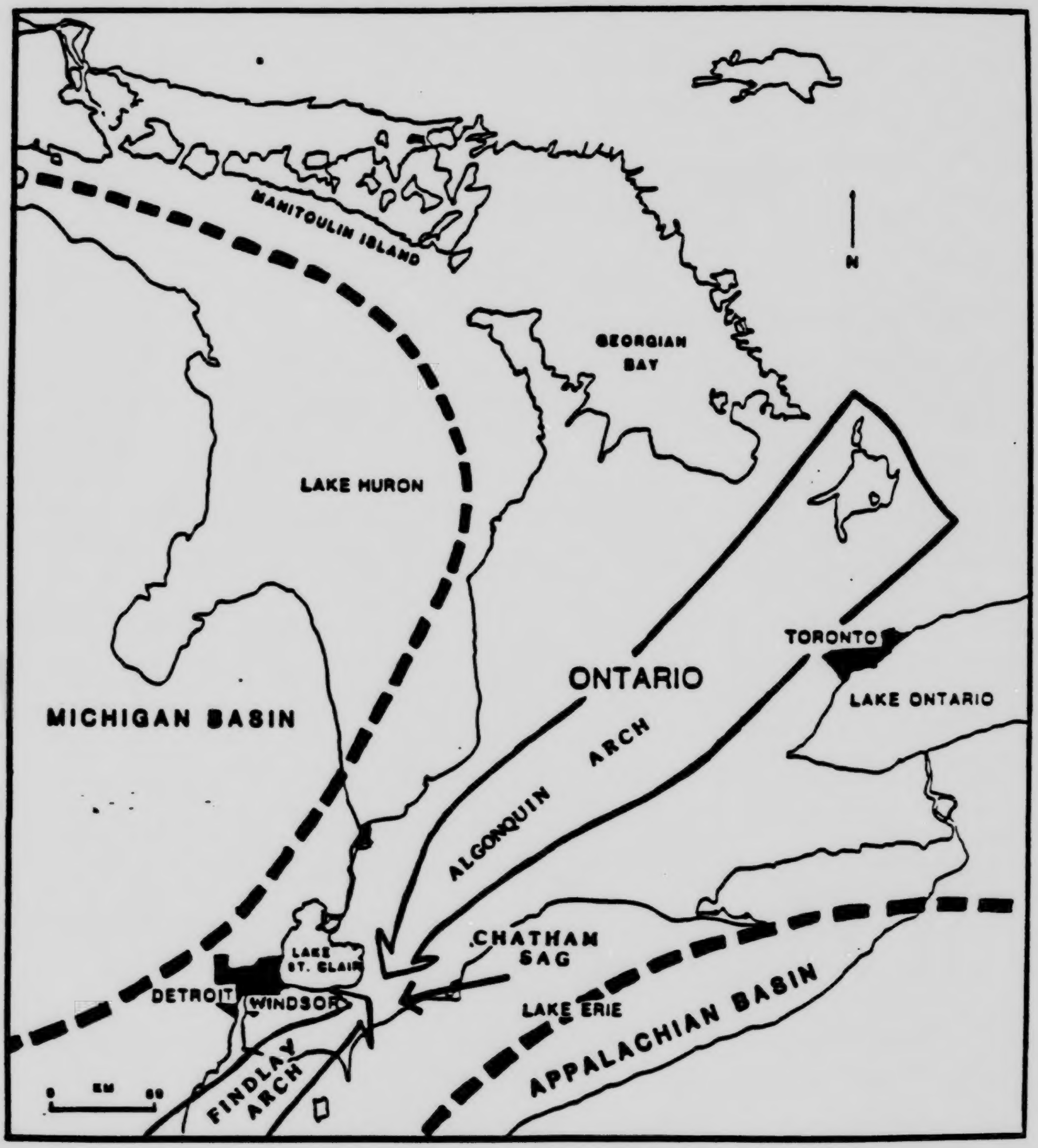

MANITOULIN ISLAND
GEORGIAN BAY
N
LAKE HURON
TORONTO
ONTARIO
LAKE ONTARIO
MICHIGAN BASIN
ALGONQUIN ARCH
LAKE ST. CLAIR
CHATHAM SAG
DETROIT
WINDSOR
LAKE ERIE
APPALACHIAN BASIN
FINDLAY ARCH
0 KM 50

Fig. 2. Major structural and paleogeographic elements in southern Ontario.

The Algonquin Arch trends in a southwest direction beneath southern Ontario, forming a broad positive lineament from which the overlying Paleozoic strata dip westward into the Michigan Basin or southward into that part of the Appalachian Basin which is commonly termed the Allegheny Trough (e.g. Winder and Sanford 1972). Within the central Michigan Basin the Paleozoic strata reach a maximum thickness of about 4,300 m. Within the Allegheny Trough, in Pennsylvania and West Virginia, the Paleozoic sequence is up to 6,700 m in thickness. In contrast, the maximum thickness of Paleozoic strata in southwestern Ontario (at the southern end of Lake Huron) is about 1,525 m (Winder and Sanford 1972).

The Findlay Arch (Fig. 2) trends obliquely to the Algonquin Arch, extending through western Ohio, southeastern Indiana, and beneath the extreme western part of southern Ontario. The two arches are separated by the Chatham Sag (Fig. 2), which is a locally developed broad depression within which the Paleozoic strata are generally horizontal. Away from the Chatham Sag and the crests of the two arches, Paleozoic strata have a consistent regional dip of 5.5 to 8.5 m per km into the Michigan Basin or Allegheny Trough (Winder and Sanford 1972).

Upper Cambrian and Lower Ordovician strata of the initial Paleozoic marine transgression in the southern Ontario region are truncated against the southeastern flank of the Algonquin Arch. This, together with the onlap and overlap of subsequent

Middle Ordovician carbonates over the arch, confirms that it was a positive topographic feature in early Paleozoic time. The arch apparently maintained its positive nature, to varying degrees, throughout much of Paleozoic time and had considerable influence, in particular, on deposition of the Devonian units of southwestern Ontario. Consequently, the Paleozoic sequence is complicated by major facies changes as strata typical of the Appalachian Basin (or Allegheny Trough) interfinger with strata typical of the Michigan Basin in complex onlap-offlap patterns over the Algonquin Arch and through the Chatham Sag. Figure 1 illustrates the Paleozoic geology of southern Ontario with its apparently simple arrangement of northwest to southeast and east striking stratigraphic units. Figure 3 demonstrates the more complex facies variations actually occurring within and between the Devonian units of the succession.

Recently, a more complicated picture of the structural geology of the Paleozoic strata of southwestern Ontario has emerged. This region has long been considered to be tectonically inactive and to have undergone very little structural disturbance during its geological history. Thus, very little attention has been given to the occurrence or significance of faults and fracture systems within the Paleozoic strata.

However, using modern Landsat imagery, data on major and minor earthquake distribution, and conventional subsurface

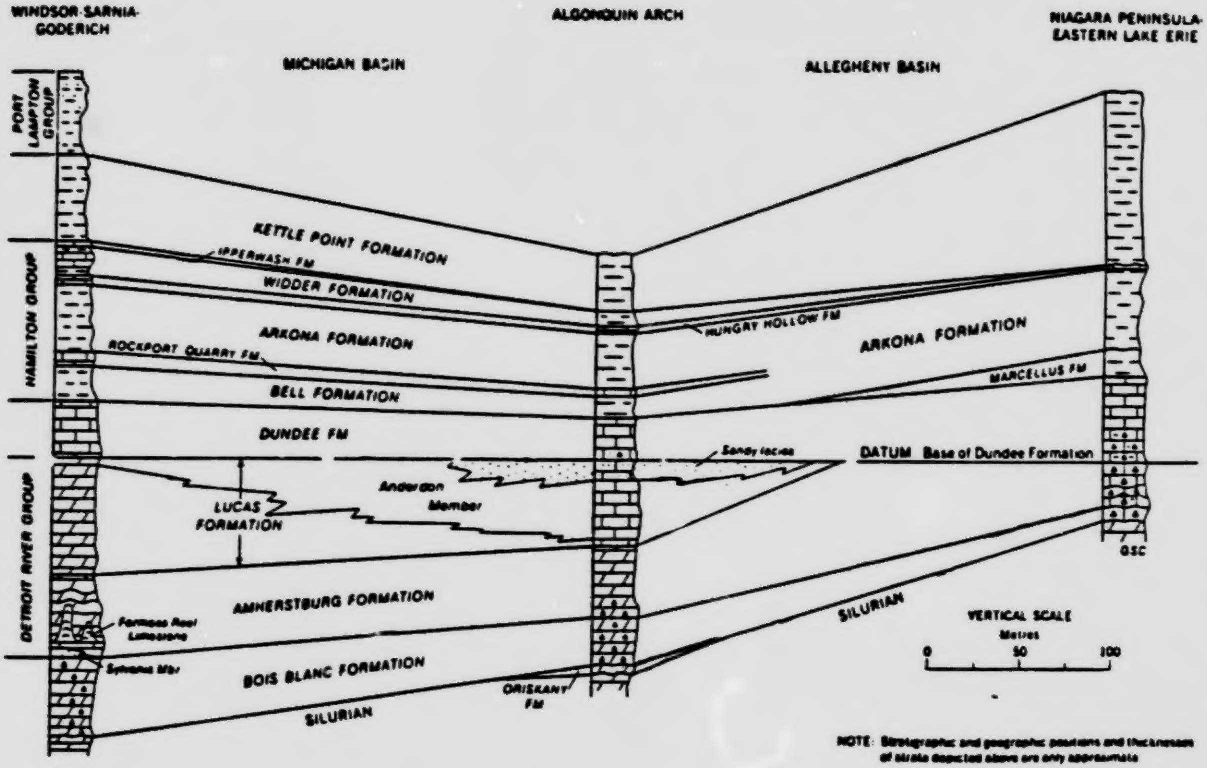

WINDSOR-SARNIA-GODERICH
ALGONQUIN ARCH
NIAGARA PENINSULA-EASTERN LAKE ERIE
MICHIGAN BASIN
ALLEGHENY BASIN
PORT LAMPTON GROUP
HAMILTON GROUP
DETROIT RIVER GROUP
KETTLE POINT FORMATION
IPPERWASH FM
WIDDER FORMATION
ARKONA FORMATION
ROCKPORT QUARRY FM
BELL FORMATION
DUNDEE FM
HUNGRY HOLLOW FM
ARKONA FORMATION
MARCELLUS FM
Sandy facies
DATUM Base of Dundee Formation
Anderdon Member
LUCAS FORMATION
AMHERSTBURG FORMATION
Formosa Reef Limestone
Sylvania Mbr
BOIS BLANC FORMATION
ORISKANY FM
SILURIAN
SILURIAN
GSC
VERTICAL SCALE
Metres
0
50
100
NOTE: Stratigraphic and geographic positions and thicknesses of strata depicted above are only approximate

Fig. 3. Devonian succession of southwestern Ontario (after Uyeno et al. 1982).

information (which is abundant for many areas in southwestern Ontario), combined with current theories of plate tectonics, Sanford et al. (1985) have developed an important new interpretation for the structural geology of the Paleozoic sequence in the region. They suggest that broad segments of the craton, underlying such areas as the Michigan Basin, were in intermittent motion through most of the Paleozoic and that some segments (e.g. Algonquin Arch region) are still mildly tectonic. They further suggest that basement arch movements and basin development in southwestern Ontario and adjacent areas may have been related to crustal plate motions and associated orogenic activity centred at or beyond the actual margins of the craton.

Re-examination of surface and subsurface stratigraphic data from southwestern Ontario in the light of these interpretations has led to a new detailed picture of probable faults and fracture systems within the Paleozoic succession (Sanford et al. 1985, Fig. 12). Southwestern Ontario is considered to occupy parts of two fault-blocks, the Bruce and Niagara megablocks (Fig. 4). The boundary between the blocks is approximately coincident with the Algonquin Arch. The Bruce Megablock was interpreted by Sanford et al. (1985, p. 59) to have been less active and was described as having a relatively simple system of east-west trending fractures within the Paleozoic strata. The more active Niagara Megablock was described as having a correspondingly more complex system of three fracture sets.

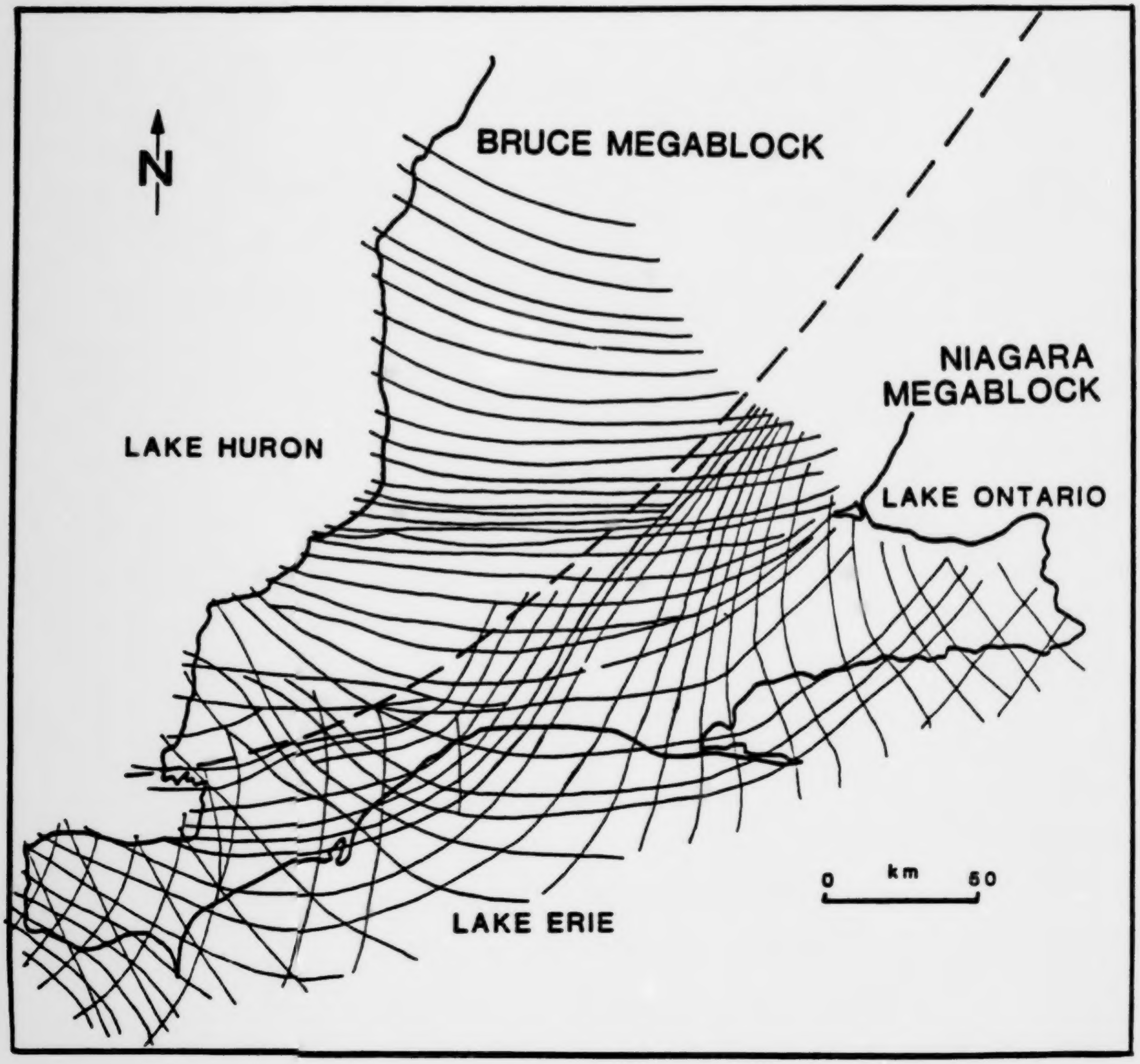

N
BRUCE MEGABLOCK
NIAGARA MEGABLOCK
LAKE HURON
LAKE ONTARIO
LAKE ERIE
0 km 50

Fig. 4. Major fracture system in the Paleozoic rocks of southwestern Ontario (after Sanford *et al*. 1985).

Although additional study and testing of these models are needed they present numerous implications with respect to the occurrence of hydrocarbon resources in southwestern Ontario. They also have significance to stratigraphic problems and anomalies previously thought to be the result of only depositional or facies variations caused by the alignment of the major paleogeographic elements of the region.

2.2 Stratigraphy of Southwestern Ontario

Not surprisingly, the relatively complex paleo-geographic situation and patterns of major and minor structural elements have led to a variety of stratigraphic terminology among the neighbouring jurisdictions of Ontario, New York, Ohio, and Michigan. The problem is most acute in southwestern Ontario which is geologically and geographically central, lying partly along the boundary between the Michigan and Appalachian Basins. In addition the poor exposure of all Paleozoic units in southwestern Ontario compared with the reasonably good exposure of Middle Ordovician strata in southcentral Ontario bordering the Precambrian Shield, and of Silurian strata of the Niagara Escarpment (Fig. 1), has provoked the establishment of two local stratigraphic schemes based on subsurface and surface data respectively.

The large volume of drilling carried out as part of the Oil Shale Assessment Project, and other O.G.S. projects in southern Ontario, has included the acquisition of twelve complete cores and downhole geophysical logs through the Paleozoic sequence (Fig. 5). This has provided an important supplement to the O.G.S. program of modern surface geological mapping of southern Ontario begun in the early 1970's. Thus, as reported by Telford _et_ _al_. (1984), the O.G.S. is now attempting to rationalize the conflicting surface and subsurface terminology in Ontario as a contribution to standardizing the Paleozoic stratigraphic nomenclature of the Great Lakes region. The work is far from complete. However, the stratigraphic terminology used below and elsewhere in this report reflects the most current usage by O.G.S. (Table 2).

Upper Cambrian/Lower Ordovician. The timing and character of the earliest Paleozoic marine transgression into the southern Ontario region are not well understood. Except for sporadic outcrops of clastic rocks on the eastern and western flanks of the Frontenac Arch (Fig. 1), Upper Cambrian or Lower Ordovician strata are restricted to the subsurface. In southwestern Ontario, these basal units pinch out on the flanks of the Algonquin Arch and are overlapped unconformably by Middle Ordovician carbonate units (see below).

From their zero edge on the southeastern side of the Algonquin Arch, the Cambro-Ordovician units increase in thickness to about 155 m beneath the Ontario portion of Lake

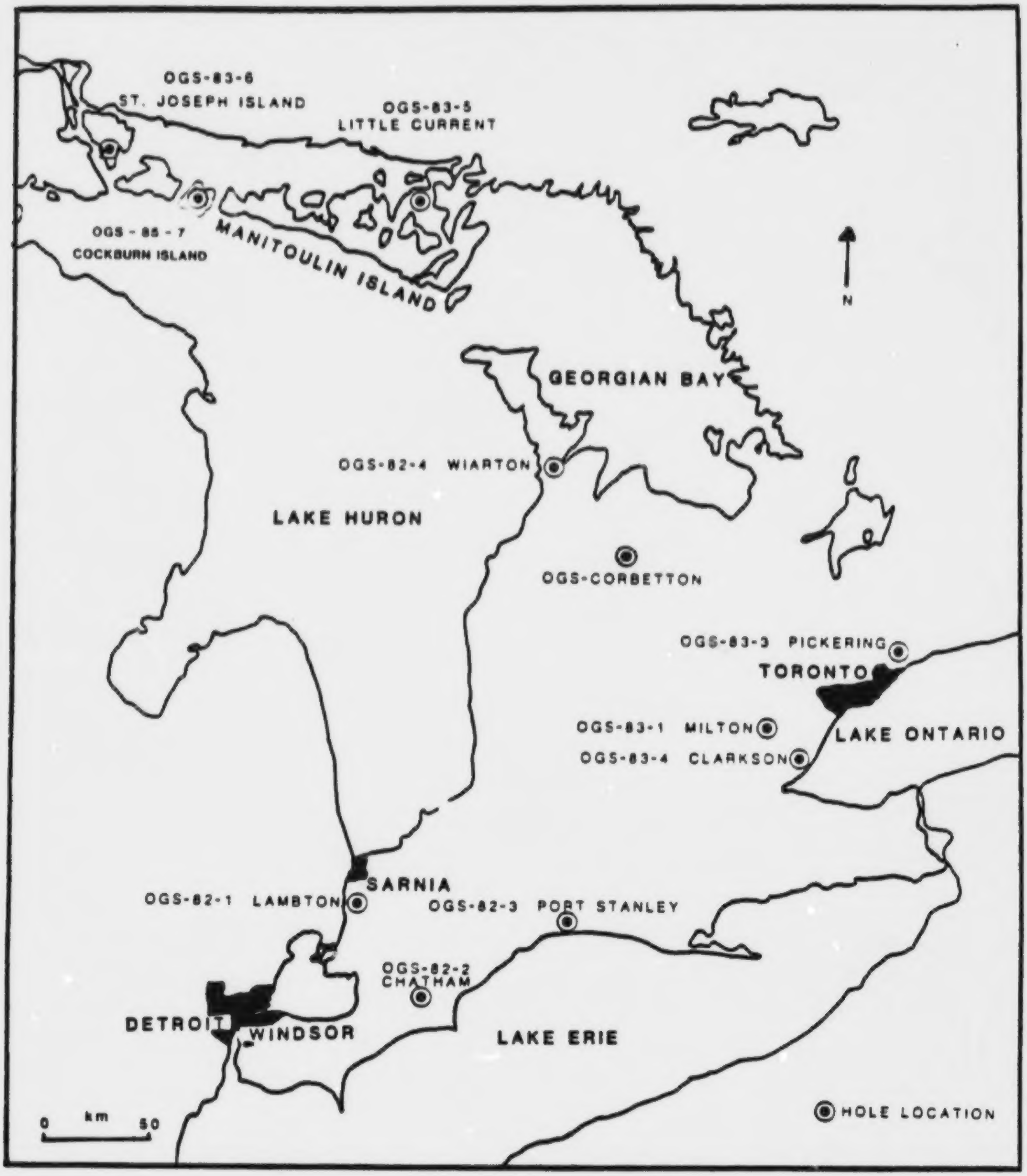
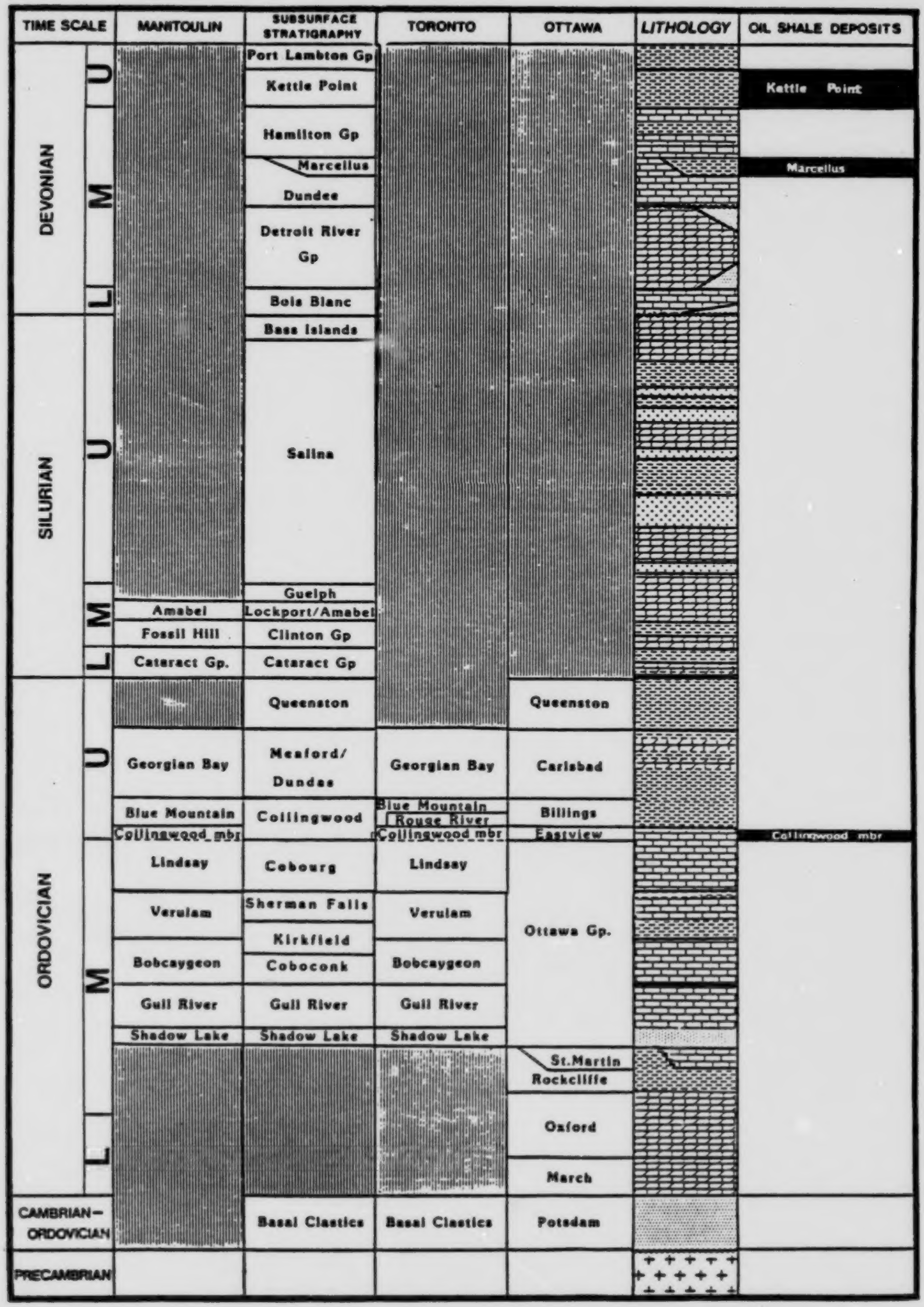

OGS-83-6
ST. JOSEPH ISLAND
OGS-83-5
LITTLE CURRENT
OGS - 85 - 7
COCKBURN ISLAND
MANITOULIN ISLAND
N
GEORGIAN BAY
OGS-82-4 WIARTON
LAKE HURON
OGS-CORBETTON
OGS-83-3 PICKERING
TORONTO
OGS-83-1 MILTON
LAKE ONTARIO
OGS-83-4 CLARKSON
SARNIA
OGS-82-1 LAMBTON
OGS-82-3 PORT STANLEY
OGS-82-2
CHATHAM
DETROIT
WINDSOR
LAKE ERIE
0 km 50
HOLE LOCATION

Fig. 5. Location of deep drillholes of the Oil Shale Assessment Project.

Erie and reach a maximum thickness of about 2,200 m in the central Appalachian Basin. On the northwestern side of the Arch, in Ontario, they have a thickness of about 77 m and reach a maximum thickness of 620 m in the southcentral Michigan Basin (Sanford and Quillian, 1959; Winder and Sanford, 1972). On both sides of the Arch a similar sequence of lithologies occurs - basal conglomerates and sandstones grading upward to interbedded sandstones and grey shaly dolostones in turn overlain by brown dolostone. Recent drilling by the O.G.S. on Cockburn Island, on the extreme northern rim of the Michigan Basin, encountered a similar lithological pattern (Wolf, 1986). Appalachian Basin and Michigan Basin stratigraphic terminology has been applied to the sequence on the southeastern and northwestern sides respectively, of the Algonquin Arch (Table 2).

There is little doubt that these basal units are markedly diachronous but, because of a lack of paleontological evidence, their age in southern Ontario is uncertain. On the basis of subsurface continuity with rocks of known Cambrian age in Wisconsin and New York State, Winder and Sanford (1972) favoured an Upper Cambrian age. Because of the marked diachroneity and the Middle Ordovician age of overlying strata, other workers have proposed a Lower Ordovician age.

Recently there has been increased interest in the basal Cambro-Ordovician sandstones for their potential oil and gas



TIME SCALE		MANITOULIN	SUBSURFACE STRATIGRAPHY	TORONTO	OTTAWA	LITHOLOGY	OIL SHALE DEPOSITS
DEVONIAN	U		Port Lambton Gp				
			Kettle Point				Kettle Point
	M		Hamilton Gp				
			Marcellus				Marcellus
			Dundee				
			Detroit River Gp				
	L		Bois Blanc				
SILURIAN	U		Bass Islands				
			Salina				
	M		Guelph				
		Amabel	Lockport/Amabel				
		Fossil Hill	Clinton Gp				
	L	Cataract Gp.	Cataract Gp				
ORDOVICIAN	U		Queenston		Queenston		
		Georgian Bay	Meaford/ Dundas	Georgian Bay	Carlsbad		
		Blue Mountain	Collingwood	Blue Mountain Rouge River	Billings		
		Collingwood mbr		Collingwood mbr	Eastview		Collingwood mbr
	M	Lindsay	Cobourg	Lindsay	Ottawa Gp.		
		Verulam	Sherman Falls Kirkfield	Verulam			
		Bobcaygeon	Coboconk	Bobcaygeon			
		Gull River	Gull River	Gull River			
		Shadow Lake	Shadow Lake	Shadow Lake			
					St.Martin Rockcliffe		
	L				Oxford		
					March		
CAMBRIAN–ORDOVICIAN			Basal Clastics	Basal Clastics	Potsdam		
PRECAMBRIAN							

Table 2. Paleozoic stratigraphic nomenclature currently in use by the O.G.S.

resources. Previous hydrocarbon discoveries were reviewed by Winder and Sanford (1972). An O.G.S. deep drillhole near Port Stanley (Fig. 5), completed in 1983 as part of the Oil Shale Assessment Project (OGS 82-3; Johnson et al., 1985), penetrated 36.8 m of Cambro-Ordovician strata within which was encountered a good show of oil in the depth interval 1125 to 1135 m. This stimulated considerable interest from the petroleum exploration community.

Middle Ordovician. Following an Early Ordovician erosional interval, the Middle Ordovician marine transgression of southwestern Ontario was very extensive and the entire region was blanketed by a comparatively thick succession of shallow water, shelf carbonate deposits. The facies variations inherent in such a depositional system have produced a complex stratigraphy with lithological changes occurring both along strike and down-dip into the Appalachian and Michigan Basins. However, the Middle Ordovician units are exposed only along a narrow zone, bordering the Precambrian shield, extending from eastern Lake Ontario to Georgian Bay and thence along the northern edges of the islands in northern Lake Huron. Therefore, only the shallower water, basin margin carbonate deposits can be examined in outcrop. The deeper water facies, and those closer to sources of terrigenous sediments from the eastern side of the Appalachian Basin can be examined only with subsurface data. Consequently, at least three stratigraphic nomenclature systems (covering the southcentral Ontario outcrop belt, northern Lake Huron outcrop belt, and southwestern Ontario subsurface, respectively) may be necessary to adequately describe the Middle Ordovician carbonate sequence.

A preliminary version of this practice was attempted in describing the Middle Ordovician portions of the deep drillcores obtained during the Oil Shale Assessment Project. Terminology proposed by Liberty (1969) was used for drillholes at Wiarton (OGS 82-4; Johnson _et_ _al_. 1985), Corbetton (Johnson _et_ _al_. 1983), and in the Toronto region (OGS 83-1 to 3; Johnson 1983) which lie within or close to the southcentral Ontario outcrop belt. Subsurface terminology proposed by Sanford (1961) and Beards (1967) was used for drillholes near Sarnia (OGS 82-1), Chatham (OGS 82-2), and Port Stanley (OGS 82-3) (Johnson _et_ _al_. 1985). Middle Ordovician carbonates were left undifferentiated in the lithological logs for drillholes on Manitoulin and St. Joseph Islands (OGS 83-5 and 6 respectively; Johnson _et_ _al_. 1985) and on Cockburn Island (OGS 85-7; Wolf 1986). Table 3 summarizes the stratigraphic thickness and terminology of Middle Ordovician carbonate units penetrated in these drillholes. The thickest section encountered (289.58 m in OGS 82-1 near Sarnia) is close to the maximum thickness of 304 m reported by Winder and Sanford (1972).

The Middle Ordovician units include a full spectrum of shallow water carbonate lithologies representing supratidal, intertidal, and shallow subtidal environments. The Shadow Lake Formation or equivalent (Table 3) is a distinctly diachronous basal clastic unit of shales, siltstones and argillaceous dolostone. It is succeeded gradationally by a sequence of fine-grained to lithographic limestones and minor dolostones (e.g. Gull River Formation). The middle part of the Middle Ordovician succession is generally dominated by bioclastic limestone or calcarenite, commonly interbedded with calcareous shales. The upper part of the succession is mainly fine grained argillaceous limestone. All units except the clastic Shadow Lake Formation are richly fossiliferous, allowing precise age determinations.

The Gull River, Bobcaygeon, and Verulam Formations (or their equivalents - see Table 3) span most of the Blackriveran and Trentonian Stages of the Middle Ordovician (Barnes et al. 1981). The uppermost carbonate unit in the succession (Lindsay Formation or equivalent - Table 3) actually straddles the Middle-Upper Ordovician boundary, ranging in age from upper Trentonian to Maysvillian (Barnes et al. 1981).

The Collingwood Member of the Lindsay Formation (Russell and Telford 1983) is one of the three southern Ontario oil shales investigated in the Oil Shale Assessment Project (Table 1). It is composed of interbedded organic-rich limestone

Drill Hole Unit	Southwestern Ontario			Central Ontario					Northern Lake Huron	
	OGS-82-1 Lambton	OGS-82-2 Chatham	OGS-82-3 Port Stanley	DH-1 Corbetton	OGS-82-4 Wiarton	OGS-83-1 Milton	OGS-83-2 Clarkson	OGS-83-3 Pickering	OGS-83-5 Little Current	OGS-83-6 St. Joseph Is.
	Cobourg	Cobourg	Cobourg	Lindsay	Lindsay	Lindsay	Lindsay	Lindsay	Lindsay	Lindsay
Upper contact elev. m.	100.96	899.46	860.00	485.76	292.76	436.46	275.46	43.65	109.70	158.45
Lower contact elev. m.	1096.35	934.28	905.00	494.94	327.70	503.64	340.61	81.46	115.35	169.00
	Sherman Falls	Sherman Falls	Sherman Falls	Verulam	Verulam	Verulam	Verulam	Verulam	Undifferentiated	Undifferentiated
Upper contact elev. m	1096.35	934.28	905.00	494.94	327.70	503.64	340.61	81.46	115.35	169.00
Lower contact elev. m.	1129.28	978.10	933.90	539.47	382.98	549.89	433.09	147.80	208.38	328.96
	Kirkfield	Kirkfield	Kirkfield							
Upper contact elev. m.	1129.28	978.10	933.90							
Lower contact elev. m.	1189.60	1028.92	992.73							
	Coboconk	Coboconk	Cococonk	Bobcaygeon	Bobcaygeon	Bobcaygeon	Bobcaygeon	Bobcaygeon		
Upper contact elev. m.	1189.60	1028.92	992.73	539.47	382.98	549.89	433.09	147.80		
Lower contact elev. m.	1199.85	1060.09	1028.15	566.72	396.24	595.98	440.43	198.35		
	Gull River	Gull River	Gull River	Gull River	Gull River	Gull River	Gull River	Gull River		
Upper contact elev. m.	1199.85	1060.09	1028.15	566.72	396.24	595.98	440.43	198.35		
Lower contact elev. m.	1336.25	1169.63	1098.80	597.72	416.66	630.17	473.44	227.19		
	Shadow Lake	Shadow Lake	Shadow Lake	Shadow Lake	Shadow Lake	Shadow Lake	Shadow Lake	Shadow Lake	Undifferentiated (Shadow Lake)	
Upper contact elev. m.	1336.25	1169.63	1098.80	597.72	415.66	630.17	473.44	227.19	208.38	
Lower contact elev. m.	1346.53	1175.00	1107.47	602.79	422.72	637.45	484.78	236.54	213.30	

TABLE 3. MIDDLE ORDOVICIAN CARBONATE UNITS INTERSECTED IN DEEP DRILLHOLES OF THE OIL SHALES ASSESSMENT PROJECT (from Johnson 1985)

and highly calcareous shale forming the upper part of the Lindsay Formation and thus representing the final phase of the Middle (to Upper) Ordovician carbonate depositional sequence in southern Ontario. The Collingwood Member as defined by Russell and Telford (1983) is not equivalent to the Collingwood Formation of Sanford (1961) identified in the subsurface of southwestern Ontario (see Table 2). The latter should probably be termed the Blue Mountain Formation. The Collingwood Member is essentially a facies within the upper part of the Lindsay Formation and is largely restricted in distribution to a zone north of a line running approximately east-west through Toronto (Russell and Telford 1983, Fig. 6).

Upper Ordovician. A major change in sedimentation patterns took place during the Late Ordovician. The Taconic Orogeny of eastern North America, coupled with a eustatic sea level drop caused by a continental glaciation on the north African craton (Dennison 1976), had a profound effect on the character and distribution of sediments in the Appalachian and Michigan Basins. Erosion of the newly created highlands encroaching into the eastern side of the Appalachian Basin shed large volumes of terrigenous material into the now shallower epicontinental seas. This is clearly illustrated in southern Ontario where the Middle (to Upper) Ordovician carbonate sequence is followed by a thick succession of shales and related terrigenous clastic units.

The Lindsay Formation is overlain disconformably by blue-grey and brown, predominantly noncalcareous shales of the Blue Mountain Formation. Thicknesses of 40-60 m for the Blue Mountain Formation were recorded during the deep drilling program of the Oil Shale Assessment Project in southwestern Ontario (Johnson *et al*. 1985). The overlying Georgian Bay Formation is a thick sequence of grey-green shales, siltstones, and minor limestones. The abundance of carbonate horizons increases to the north (i.e. away from the southeastern source of terrigenous sediments) and, on Manitoulin Island, the upper or Kagawong Member of the formation is dominantly bioclastic and argillaceous limestones and dolostone (Johnson and Telford 1985). The unit is over 250 m thick in the Toronto region (Johnson 1983) but thins to less than 100 m in southwestern Ontario and northern Lake Huron (Johnson *et al*. 1985).

The uppermost Ordovician unit in southern Ontario is the Queenston Formation, a thick sequence of red and maroon siltstones and shales that was deposited as the distal fine-grained element of a major deltaic complex extending from the eastern margin of the Appalachian Basin. The unit reaches a maximum thickness in Ontario (under eastern Lake Erie) of 341 m (Winder and Sanford 1972). Northeastwards, the red clastic unit thins and grades laterally into the grey shales and carbonates of the upper Georgian Bay Formation.

The Blue Mountain-Georgian Bay-Queenston sequence is upper Maysvillian to Richmondian in age (Barnes *et al*. 1981). Strata representing the youngest Ordovician Gamachian Stage are not present in southwestern Ontario or adjacent areas, thus showing that the Late Ordovician global sea level drop was sufficient to produce a significant hiatus in the region before marine transgression again took place in the Early Silurian.

Lower-Middle Silurian. The Silurian strata of southwestern Ontario constitute the most intensely studied and best understood sequence in the region. This is due in part to the excellent exposures of Lower and Middle Silurian rocks in the Niagara Escarpment (Fig. 1) and to the considerable interest in exploration and development of oil and gas resources from several of the stratigraphic units.

The Niagara Escarpment is a prominent cuesta which separates lowlands underlain by Ordovician strata to the east from uplands of Silurian, and eventually Devonian, rocks in the west. It first appears as a distinct geological and topographical feature near Rochester, New York State. Paralleling the south shore of Lake Ontario, the Escarpment enters Ontario at Queenston Heights and extends westward to Hamilton. It swings to the north, extending to the Blue Mountain area near Collingwood on southern Georgian Bay, and then continues in a very serrated fashion northwestwards to Wiarton. North of Wiarton it forms the spectacular eastern shore of the Bruce Peninsula as far as Tobermory where it dips beneath the waters of Lake Huron. Reappearing on the north side of Manitoulin Island, the Escarpment continues northwestward as a more subdued topographic feature and eventually passes into the northern peninsula of the State of Michigan.

The Escarpment extends from the Appalachian Basin, over the Algonquin Arch, and into the Michigan Basin, thus exposing the variety of lower and Middle Silurian lithologies and complex facies associations which characterize these geological provinces. During the Silurian the Michigan Basin was mainly a carbonate and evaporite basin whereas sediments in the adjacent Appalachian Basin were largely clastics with less abundant carbonates.

Bolton (1957) provided the first fully comprehensive account of the stratigraphy of the Niagara Escarpment in southern Ontario. Martini (1971) examined the Lower Silurian part of the sequence in the Niagara Peninsula and western New York State, showing that this dominantly clastic sequence was formed in deltaic and prodeltaic environments. Lower and Middle Silurian strata in the subsurface of southwestern Ontario were described by Sanford (1969a), who interpreted the complex carbonate shelf, bank, and reefal lithofacies. A more recent summary of the Niagara Escarpment sequence in southern Ontario was provided by Telford (1978) and new maps of the

Silurian geology on Manitoulin Island have been released by the Ontario Geological Survey (e.g. Johnson and Telford 1985).

Because of the diverse facies associations, total thicknesses of the Lower-Middle Silurian strata in southwestern Ontario are variable, ranging from almost 300 m beneath eastern Lake Erie and northern Lake Huron to less than 100 m in the Sarnia area (e.g. OGS drillhole 82-1 -Johnson et al. 1985) and the Niagara Peninsula. The thickest sequences occur in former shelf areas around the rim of the Michigan Basin where there was major carbonate bank and reefal development (Sanford 1969a). The classic section in Niagara Gorge extending from the basal Silurian Whirlpool Formation to the Middle Silurian Lockport Formation is about 85 m in thickness (Telford 1978).

More than 90% of the gas production and about half of the oil production to date in Ontario has come from Silurian rocks. Most of the oil has been extracted from Middle Silurian reefal carbonates of the Guelph Formation and closely overlying carbonates of the Upper Silurian Salina Formation (Rybansky and Trevail, 1983). Powell et al. (1984) suggest that the principal source of these hydrocarbons was the Middle Silurian Eramosa Member of the Amabel Formation (Table 2). The dark laminated dolostones of the Eramosa Member were formed in restricted inter-reefal zones and, with organic carbon contents ranging to about 3% (Powell et al. 1984), the unit could be classed as a potential "oil shale". It was not investigated in the Oil Shale Assessment Project due to its relatively low organic content.

Upper Silurian. The Late Silurian was, again, a time of contraction of the epicontinental seas in eastern North America, and evaporitic conditions were strongly developed in the Michigan Basin and adjacent areas. In southwestern Ontario the Upper Silurian Salina Formation consists of salt (halite), gypsum, and anhydrite units alternating with dolostone, limestone, and shale. Near the southern end of Lake Huron, salt beds in the Salina Formation have a composite thickness of over 200 m (Winder and Sanford, 1972). The current subsurface distribution of the salt beds is considered to be much reduced from their original depositional extent (Sanford 1969a). This is the result of gradual dissolution of the salt which began in the Late Silurian along the margins of the Michigan Basin and continued basinward through successive periods of geological time. Sanford et al. (1985) have demonstrated a close relationship between the salt dissolution patterns and major fracture systems in southwestern Ontario.

The Salina Formation is conformably overlain by dolostone of the Bass Islands Formation (called Bertie Formation on the Niagara Peninsula). This is the youngest Silurian unit in southern Ontario and its top is an erosional surface signifying a major hiatus and period of subaerial exposure. Sand grains and other sediments from overlying Devonian formations are often present in cracks and joints for several metres into the upper part of this unit (Telford and Johnson 1984).

The maximum combined thickness of the Salina and Bass Islands Formations is 518 m near southern Lake Huron but the sequence thins to only 105 m over the Algonquin Arch (Winder and Sanford, 1972). In OGS drillhole 82-1 near Sarnia (Fig. 5), the Salina Formation was 330 m thick and the Bass Islands Formation was 24 m thick (Johnson et al. 1985).

Age determinations and regional correlations of the Lower-Middle Silurian and especially the Upper Silurian formations are not as precise as the underlying Ordovician and overlying Devonian units. For example, correlation of the mainly unfossiliferous Salina and Bass Islands Formations is based only on the stratigraphic positions of these units. See Telford (1978) and Winder *et al*. (1975) for further review of this situation.

Lower Devonian. In southwestern Ontario, the Lower Devonian was mainly a time of emergence and erosion. The oldest Devonian strata of the region are quartzitic sandstones of the Oriskany Formation which occur as erosional remnants in depressions on the irregular Upper Silurian surface. The formation has been positively identified at only one locality in Ontario, outcropping in an approximately 600 hectare area, 10 km east of Hagersville (Fig. 1; Winder and Sanford, 1972; Uyeno *et al*., 1982; Telford and Johnson, 1984). Sanford (1968) suggested that the formation may be present elsewhere in the subsurface of southwestern Ontario. Sandstones of the

Oriskany have a wide distribution in the Appalachian Basin and the Ontario occurrences are probably close to the northern depositional edge of the unit.

The Oriskany Formation was deposited during the middle Early Devonian (Pragian) and was, in turn, subjected to erosion before deposition of the overlying Bois Blanc Formation during the late Early Devonian. The Bois Blanc Formation is an eastward thinning carbonate wedge, up to 50 m thick in southwestern Ontario, and only 3-15 m thick on the Niagara Peninsula (Uyeno _et_ _al_. 1982). It is essentially a Michigan Basin rock unit which spilled over the Algonquin Arch and overlapped and intertongued with clastic and carbonate units of the Appalachian Basin. The Bois Blanc consists of argillaceous fossiliferous limestone, dolomitic limestone, abundant chert, and a glauconitic sandy facies sporadically developed in its basal part.

Lower-Middle Devonian carbonates. Overlying the Bois Blanc Formation is a variable sequence of limestones and dolostones of upper Lower to lower Middle Devonian age. On the Niagara Peninsula, the Bois Blanc is overlain with possible disconformity by coral-rich biostromal limestones of the Edgecliff Member of the Onondaga Formation (Telford and Tarrant, 1975b). In western New York State the Onondaga Formation has been divided into four limestone members (in ascending order: Edgecliff, Clarence, Moorehouse, and Seneca - see Oliver 1976) and the lower three can be traced into the Niagara Peninsula of Ontario, as far west as Port Dover

(Telford and Tarrant 1975a, b; Telford and Hamblin 1980). Farther west, the Appalachian Basin Onondaga limestones grade laterally into limestones and dolostones of the Michigan Basin Detroit River Group.

The lower unit of the Detroit River Group is the Amherstburg Formation which consists of bituminous, chert-rich, bioclastic limestone. Its lateral relationships with the Onondaga Formation are not clear because of a lack of outcrops and subsurface data in key areas. Its contact relationships with the underlying Bois Blanc Formation are poorly understood because the lithological similarities between the units preclude accurate discrimination in subsurface records (Beards 1967). Around the southern part of the Michigan Basin, in Ontario (Windsor-Essex area) and Michigan, the carbonates of the lower Amherstburg intertongue with strand-line and aeolian quartzitic sandstones of the Sylvania Member. To the north, in Bruce and Huron Counties, the Amherstburg contains extensive reefal deposits (Sanford, 1968). Termed the Formosa Reef Limestone, these reefs and bioherms were part of a large platform reef development which characterized the south-eastern rim of the Michigan Basin during the time of Amherstburg deposition. Toward the centre of the Michigan Basin the Amherstburg is largely a dolomitic unit.

Conformably overlying the Amherstburg Formation is the Lucas Formation, a complex unit with a variety of lithologies. In the central Michigan Basin it is basically an evaporite, made up of salt and anhydrite interbedded with anhydritic dolostones and limestones (Sanford, 1968). Around the margins of the basin, such as the Algonquin Arch region of southwestern Ontario, the formation consists of shallow shelf carbonate deposits of dolostones and high purity limestones. The latter are quarried extensively in the Woodstock-Ingersoll and Amherstburg areas for use in the cement, steel and chemical industries. The high purity limestone facies is often termed the Anderdon Member (Uyeno et al. 1982). Near Ingersoll the upper part of the Anderdon Member is characterized by a distinctive sandy limestone facies.

The Lucas Formation pinches out rapidly to the east and, in the Simcoe area, the Dundee Formation directly overlies the older Amherstburg or Onondaga Formations (Telford and Hamblin 1980). In Ontario, near the southern end of Lake Huron, thicknesses of 62 m and 93 m respectively have been recorded for the Amherstburg and Lucas Formations (Winder and Sanford 1972). In OGS drillhole 82-1 near Sarnia (Fig. 5), the total thickness of the Detroit River Group was 120.65 m (Johnson et al., 1985).

Overlying the units of the Detroit River Group with probable slight disconformity are richly fossiliferous micritic limestones of the Dundee Formation. This unit forms the bedrock of a broad belt extending across southwestern Ontario from central Lake Erie to Lake Huron; it also underlies part of the Windsor-Essex area and Pelee Island in Lake Erie (Fig. 1). The Dundee is correlative, in part, with the Delaware Formation of Ohio and the upper part of the Onondaga Formation in New York (Uyeno et al. 1982). The Tioga Ash Bed, which separates the Moorehouse and Seneca Members of the Onondaga Formation in New York and is a widely used marker horizon in the Appalachian Basin, may be present in the lower part of the Dundee Formation but positive confirmation is still required (Sanford 1968; Uyeno et al. 1982, p.16).

The Dundee Formation has a maximum thickness of 120 m in the Saginaw Bay area of Michigan (Sanford 1968) but is considerably thinner in southwestern Ontario. Thicknesses of 35-45 m were recorded during the deep drilling phase of the Oil Shale Assessment Project (Johnson et al. 1985).

Formations of the Detroit River Group are considered to be of uppermost Lower Devonian (Emsian) age while the overlying Dundee Formation is of lower Middle Devonian (Eifelian) age. The Dundee Formation has yielded the richest and most diverse conodont fauna of any Devonian unit in southwestern Ontario (Uyeno et al. 1982). Preservation of the conodonts is extremely good and collections from the Dundee have been used in a number of important taxomonic and paleoecological studies (e.g. Ferrigno, 1971; Klapper and Philip, 1971).

The first recorded occurrences of oil in southern Ontario, in the early 1800's, were seeps from shallow reservoirs of Devonian age. The first oil well in North America was dug and drilled in 1858 at Oil Springs in southwestern Ontario, discovering crude oil in the Dundee Formation. Since then, almost 40% of Ontario's oil production has come from dolomitized zones within the Dundee or underlying Lucas Formation (Rybansky and Trevail 1983). The shallow oil pools of the Dundee continue to attract considerable interest from the local petroleum exploration industry.

Middle Devonian shales. The late Middle Devonian Acadian Orogeny in eastern North America produced significant changes to the sedimentation patterns of the Appalachian and Michigan Basins. Deposition of fine marine clastics derived from eastern land areas succeeded the widespread early Middle Devonian carbonate deposition. In southwestern Ontario, the limestones of the Dundee Formation are overlain by either black shales of the Appalachian Basin Marcellus Formation or grey shales of the Michigan Basin Bell Formation.

The principal subject of this report, the Marcellus Formation is a potential oil shale which forms the bedrock of a restricted area along the north shore of Lake Erie near Port Stanley (Fig. 1; see Chapt. 3 for stratigraphic details).

The Bell Formation is the lowermost unit of the Hamilton Group in southwestern Ontario. Overlying units in ascending order, are the Rockport Quarry (limestone), Arkona (shale), Hungry Hollow (limestone), Widder (shale, siltstone, limestone), and Ipperwash (limestone) Formations. The Hamilton Group of Ontario correlates with the middle part of the Hamilton Group in New York State and with the Traverse Group of Michigan. The Ontario rock units actually lie in a transition zone between the largely clastic units of the New York (Appalachian Basin) sequence and the largely carbonate sequence in the Michigan Basin.

Maximum total thickness of the Hamilton Group in Ontario is about 93 m (Winder and Sanford, 1972). The following formation thicknesses were measured in OGS drillhole 82-1 (Johnson _et_ _al_. 1985).

Ipperwash Formation	- 1.99 m
Widder Formation	- 21.44 m
Hungry Hollow Formation	- 2.00 m
Arkona Formation	- 32.10 m
Rockport Quarry Formation	- 5.76 m
Bell Formation	- 14.57 m
Total	- 77.86 m

The Ipperwash Formation is actually quite variable in thickness (0-13 m) because of irregular erosion of these limestones during the hiatus which preceded deposition of the overlying Kettle Point Formation (see below). The Rockport Quarry Formation is much thicker in Michigan (averaging about 20 m) and the Ontario occurrences are close to the eastern depositional edge of the unit. The richly fossiliferous Hungry Hollow Formation is noteworthy in that it maintains its low thickness over a large area and can be traced accurately in the subsurface using geophysical logs from oil and gas exploration wells (Beards, 1967; Telford 1976).

The Hamilton Group in southwestern Ontario is considered to be of lower Givetian age (Uyeno _et al_. 1982). However, paleontological data are poor for the lower units (lower Arkona down to Bell), which occur only in the subsurface, and they may range as old as upper Eifelian.

Upper Devonian. The change from carbonate-dominated to clastic-dominated deposition, which began during the Middle Devonian, culminated in the Upper Devonian with deposition of noncalcareous black shales throughout the sedimentary basins of eastern North America. In southwestern Ontario this depositional episode is represented by the Kettle Point Formation, a potential oil shale and one of the principal targets of the Oil Shale Assessment Project. The Kettle Point and its equivalents in the Michigan, Appalachian, Illinois, and Moose River Basins are known collectively as the Eastern Gas Shales and are reviewed in more detail in Chapter 2.3. The older Marcellus Formation and correlative black shales also are referred to as part of the Eastern Gas Shales sequence and are discussed in Chapter. 2.3.

Conodont studies suggest that the Kettle Point Formation, where it is fully preserved, may span almost the entire Upper

Devonian, ranging from early Frasnian to late Famennian age (Uyeno et al. 1982).

The youngest Devonian, indeed the youngest Paleozoic units in southwestern Ontario, are the formations of the Port Lambton Group. In ascending order, they consist of the Bedford (grey shales), Berea (sandstone), and Sunbury (black shale) Formations which have a combined maximum thickness in Ontario of about 62 m (Winder and Sanford 1972). They occur in the subsurface of a small area south of Sarnia bordering the St. Clair River (Fig. 1). In OGS drillhole 82-1 (Johnson et al. 1985), 33.4 m of dark grey shale referable to the Bedford Formation was present, overlying the Kettle Point Formation with probable disconformity. The age of the Port Lambton Group has been uncertain with some workers assigning it to the Upper Devonian and others suggesting Lower Mississippian. An uppermost Devonian age is now generally accepted (Uyeno et al. 1982).

2.3 Eastern Gas Shales

Middle Devonian to Lower Mississippian black shales of eastern North America directly underlie or occur in the subsurface of a large area extending from Alabama and Oklahoma in the south to Ontario and Michigan in the north and as far west as Iowa (Fig. 6). The Upper Devonian Long Rapids Formation of the Moose River Basin in northeastern Ontario, now isolated from the Paleozoic sedimentary basins in the south, probably represents the most northerly extent of the black shale deposition.

In response to the energy shortages of the early 1970's, the United States Department of Energy organized the Eastern Gas Shales Project. Its principal objective was to study the largely Devonian black shales of eastern North America particularly in reference to natural gas production. However this also led to evaluation of the shale oil potential of the units. Thus, over the past decade a prodigious body of new data has been generated which relates directly and indirectly to the O.G.S. evaluation of the oil shales in Ontario. For a review of the U.S. program and its results see Janka and Dennison (1980), Matthews (1983), Roen (1984).

The bulk of the U.S. studies have been focussed on the black shale sequences of the Appalachian Basin although considerable information has also been gathered and synthesized concerning the correlative sequences in the Illinois and Michigan Basins. An important result of the various programs has been the development of detailed stratigraphic frameworks for all of the areas of interest and the capability for precise biostratigraphic correlation of the black shale sequences within and between the basins. For example, the distinctive algal microfossil Foerstia has been recognized as a consistent stratigraphic time marker within Upper Devonian black shales of the Appalachian, Illinois, and Michigan Basins, including the Kettle Point Formation of southwestern Ontario (Matthews 1983; Russell 1985). The use

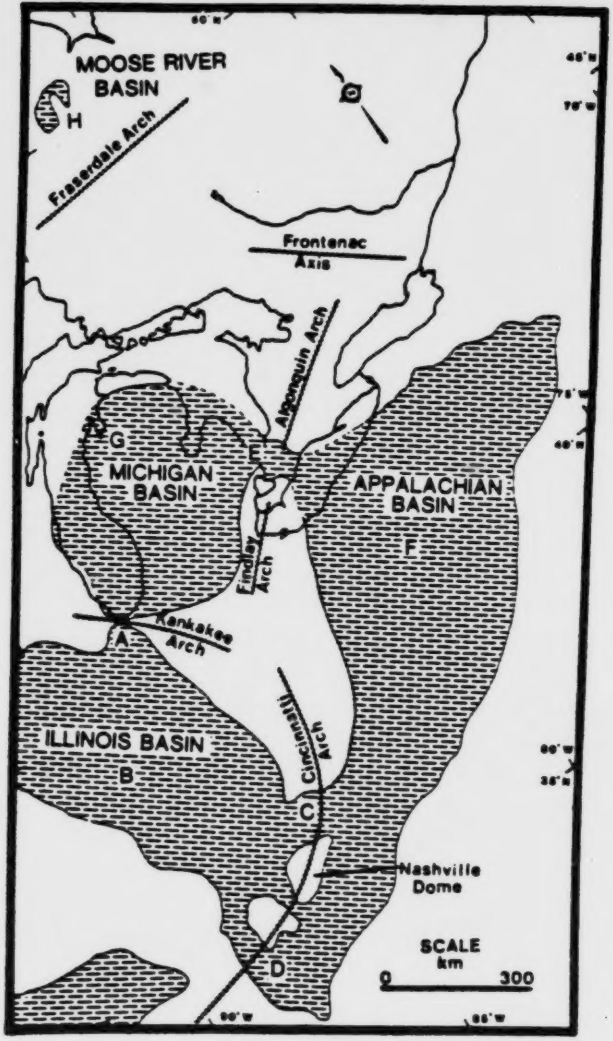

MOOSE RIVER
BASIN
H
Fraserdale Arch
Frontenac
Axis
Algonquin Arch
G
MICHIGAN
BASIN
E
APPALACHIAN
BASIN
F
Findlay
Arch
A
Kankakee
Arch
ILLINOIS BASIN
B
Cincinnati
Arch
C
Nashville
Dome
D
SCALE
km
0
300
75°W
40°N
80°W
36°N
90°W
85°W

Fig. 6 Distribution of Devonian black shale in eastern North America.

of downhole gamma-ray logs for fine subdivision of black shale sequences and for accurate lithostratigraphic correlation of sequences in adjoining areas has been demonstrated by Ells (1978) and Russell (1985). As noted by Roen (1984), the biostratigraphic and lithostratigraphic markers that have been identified, and the regional stratigraphic frameworks that have been developed, are allowing correlations with such precision that, for example, a 4-5 m shale sequence in Tennessee can be related to a 900 m shale sequence in New York State.

Within the Appalachian Basin there were essentially two phases of Devonian black shale deposition. The earlier, somewhat stratigraphically and geographically restricted, Middle Devonian phase included strata to which the Marcellus Formation of southwestern Ontario is equivalent. The later, more extensive, Upper Devonian phase includes the sequences to which Ontario's Kettle Point and Long Rapids Formations are correlative.

The general depositional histories of the Middle and Upper Devonian sequences followed a similar pattern. The shales were formed in a broad shallow waterway known as the Chattanooga Sea which covered most of the eastern United States and extended into Ontario (Janka and Dennison, 1980). This marine basin or series of basins was probably open to the south (according to present day orientation of compass directions), bounded on the east by highlands of the ancestral Appalachian Mountains, and confined in the north and west by

Precambrian and Lower Paleozoic rocks of the stable continental craton.

The global position of the North American continent during the Devonian was markedly different from its present day location. It was rotated perhaps as much as 90° from its present-day orientation and the region of the Chattanooga Sea lay at about 10° south latitude . Because of the restricted nature of the sea, stagnant conditions probably prevailed at certain times in the warm shallow waters, and, combined with prolific growth of phytoplankton and other organisms, this resulted in deposition of organic-rich sediments.

Greatest accumulation of the shales took place in the eastern part of the Chattanooga Sea in what is now referred to as the Appalachian Basin. This was mainly due to the greater influx of terrigenous sediments into this region from the nearby eastern highlands. Up to several thousand metres thickness of black shales have been recorded in West Virginia (Janka and Dennison, 1980), in the east-central Appalachian Basin. In the neighbouring Illinois and Michigan Basins, to the west and northwest respectively, only 100-300 metres thickness of shales were deposited. The depositional centres of these basins were separated from the larger Appalachian Basin by the Cincinatti, Findlay, and Algonquin Arches (Fig. 6). Although these arches and other structural highs such as the Nashville Dome did not completely impede circulation of the marine waters and sediments among the basins, they did have a significant effect on regional depositional patterns. This is exemplified by the character and distribution of the Marcellus and Kettle Point Formations in southwestern Ontario.

As discussed later in this report, the Marcellus Formation appears to wedge out against the southeastern flank of the Algonquin Arch, and equivalent Middle Devonian black shales have not been recognized in the Michigan Basin. The Kettle Point Formation, with a maximum thickness of only about 70 m, represents an area with a lower rate of sedimentation in comparison to adjoining basinal areas (Russell, 1985).

The wide geographic extent and relatively broad stratigraphic range of the Devonian shales of eastern North America have led to a plethora of formational names and other stratigraphic terms. This is inevitable as different workers operating from different conceptual bases or in geographically restricted areas have attempted to name and subdivide the shale sequences. Janka and Dennison (1980) produced a series of tables which usefully summarize the stratigraphic terminology for the eastern United States. More recently, Matthews (1983) discussed the correlation of major Upper Devonian black shale units between the Appalachian, Illinois, and Michigan Basins. As part of the O.G.S. Oil Shale

Assessment Project, Russell (1985) reviewed current terminology with respect to the Kettle Point Formation of Ontario. Rickard (1984) provided new interpretations of the correlation of the Marcellus Formation in the Lake Erie region. Figure 7 illustrates diagrammatically the relationship of the Marcellus and Kettle Point Formations of Ontario with other Devonian black shale units of eastern North America. Correlation of Ontario's Marcellus Formation with other Middle Devonian black shale sequences in the Appalachian Basin is discussed more fully in Chapter 3.6.

As well as being evaluated as a source of natural gas by the Eastern Gas Shales Project, the Devonian black shales of eastern North America have also been studied as potential uranium areas (Swanson 1960) and as disposal media for nuclear waste (Lomenick 1983). As noted previously, the Eastern Gas Shale Project has also given impetus to the assessment of the shales as a major oil shale resource. A survey by the Institute of Gas Technology, reported by Janka and Dennison (1980), estimated a surface-mineable oil shale resource in the eastern United States of 423 billion barrels of oil, based on processing the shales using the patented IGT HYTORT system. Clearly, this is a theoretical resource value and many other technical and socio-economic factors must be taken into account.

Oil yields by conventional retorting processes from the eastern shales are much lower than those from the well-known Eocene-age Green River Formation of Colorado (Robl and

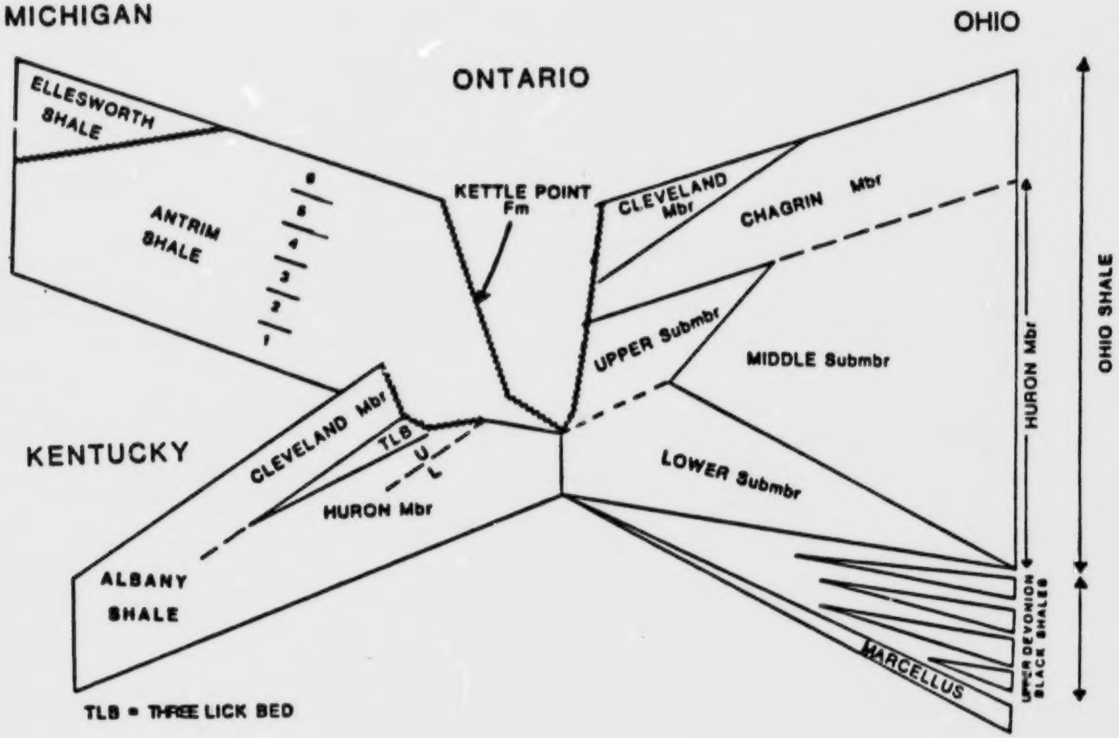

MICHIGAN
ONTARIO
OHIO
ELLESWORTH SHALE
ANTRIM SHALE
6
5
4
3
2
1
KETTLE POINT Fm
CLEVELAND Mbr
CHAGRIN Mbr
UPPER Submbr
MIDDLE Submbr
LOWER Submbr
HURON Mbr
OHIO SHALE
KENTUCKY
CLEVELAND Mbr
TLB
U
L
HURON Mbr
ALBANY SHALE
MARCELLUS
UPPER DEVONIAN BLACK SHALES
TLB = THREE LICK BED

Fig. 7. Diagrammatic representation of stratigraphic relationships of Devonian black shales of the Appalachian and Michigan Basins (after Matthews 1983).

Koppenaal 1982). Also, although the total hydrocarbon resource of the eastern shales is greater, and they are more widespread, their mineable high yield zones are usually thinner than the Colorado oil shales. Exploration of the eastern oil shales will therefore be dependent on the development of improved mining and processing technologies (see Chapter 5 for further discussion concerning exploitation of Ontario's potential oil shales). Nevertheless, the Devonian black shales of eastern North America constitute an important hydrocarbon resource whose potential impact on future energy supply scenarios cannot be ignored.

3. STRATIGRAPHY OF THE MARCELLUS FORMATION

3.1 Introduction

The Middle Devonian Marcellus Formation is one of the most poorly defined stratigraphic units in Ontario. It is not exposed in the Province and, prior to this study, was known only from dark shale well cuttings obtained from petroleum exploration wells and from poorly defined geophysical signatures (Musial 1982).

In an attempt to resolve the identity of this unit in conjunction with the aims of the Oil Shale Assessment Project, the Ontario Geological Survey undertook a detailed drilling programme of the unit during 1982-1983. Six fully cored and geophysically logged boreholes were drilled at locations where shales of the Marcellus Formation had been previously shown (Sanford 1969b) to form the bedrock surface (Fig. 8 and Table 4). Five holes were shallow, being directed specifically at the Marcellus Formation (M-5 to M-9 - see Johnson 1985), and one was extended from surface to the Precambrian to test for the presence of deeper oil shales (i.e. Collingwood Member of the Lindsay Formation) and to provide data for regional correlations (OGS 82-3 Port Stanley - see Johnson _et_ _al_. 1985).

Only four holes (M-5, M-6, M-8, and OGS 82-3) intersected strata tentatively identified as the Marcellus Formation. The uppermost bedrock in the remaining two shallow drillholes was

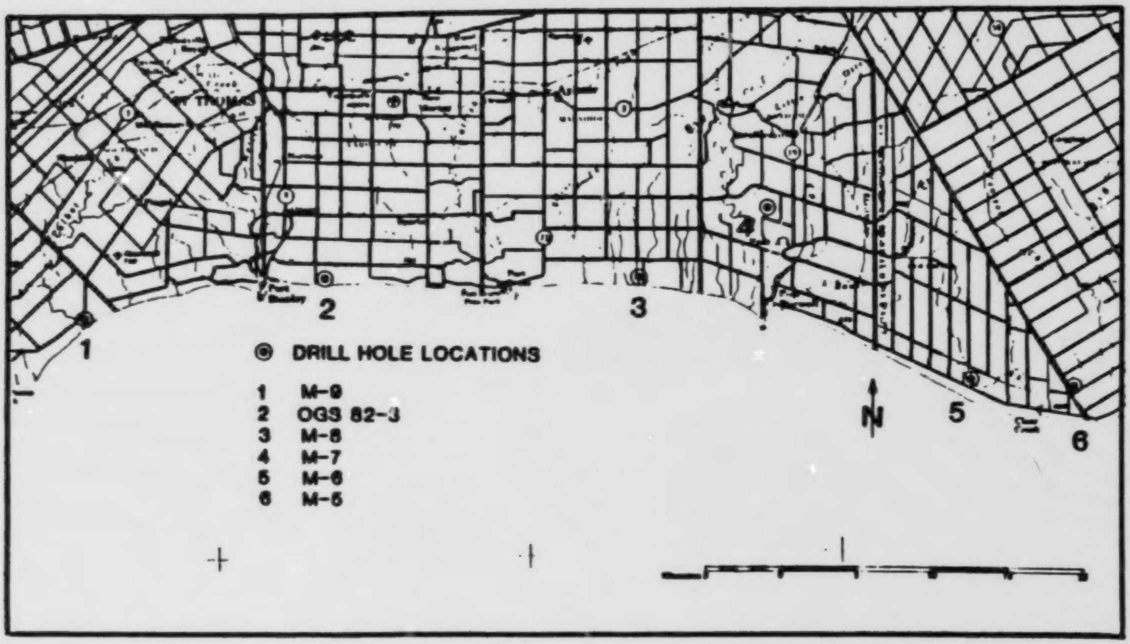

DRILL HOLE LOCATIONS
1 M-9
2 OGS 82-3
3 M-8
4 M-7
5 M-6
6 M-5
N
1
2
3
4
5
6

Fig. 8. Location of OGS drillholes, M-5 to M-9 and OGS 82-3, Port Stanley area.

Hole Number	Glacial Cover Thickness (m)	Bell Fm. (m)	Marcellus Fm. (m)	Dundee Fm. (m)	Depth to top of Marcellus (m)	Drill Hole Total Depth (m)
M-5	95.5	12.1	3.3	6.4	108.6	117.7
M-6	88.0	5.3	3.2	4.9	93.3	101.4
M-7	48.8	N/E	N/E	14.3	N/E	63.1
M-8	84.2	N/E	3.4	12.3	84.2	99.9
M-9	54.0	N/E	N/E	5.1	N/E	59.1
OGS-82-3	79.8	12.5	5.4	32.8	92.3	1165.5

N/E:- Formation not encountered in this drill hole.

TABLE 4. SUMMARY OF OGS DRILL HOLES FOR THE MARCELLUS FORMATION

the Dundee Formation which stratigraphically underlies the Marcellus. In all drillholes the bedrock was buried by thick sequences (up to 100 m) of Pleistocene glacial and glaciolacustrine sediments.

The Marcellus Formation has been previously interpreted as an elliptical lens shaped body extending below Lake Erie (Musial 1984) and to a limited extent beneath land around Port Stanley (Sanford 1969b). To minimize drilling costs and to maximize the data gathering potential, the OGS drillholes were arranged in an east-west pattern as close to the Lake Erie shoreline as possible (Fig. 8). The high cost of offshore drilling made this activity prohibitive, which unfortunately meant that the most reliable information (i.e. core samples) could only be obtained from the erosional or facies-edge of the unit (see Isopach map - back pocket).

Immediately evident from the OGS cored holes was a strong relationship between the presence of organic rich beds in the Marcellus and peaks in the natural gamma log (Johnson 1985). Thus, to augment information available from the OGS drillholes, Marcellus intervals were also interpreted, using natural gamma logs, from an additional one hundred and five oil and gas exploration wells drilled both in Lake Erie and nearby onshore areas (Appendix 3). This information was made available by the Petroleum Resources Laboratory, Ministry of Natural Resources, London, Ontario. Well cuttings from these holes were also examined. The resource evaluation (Chapter 5) is based largely on this exploration data.

3.2 Historical Review

The term "Marcellus" was first introduced by Hall (1839) for a sequence of shales and limestones containing a distinctive faunal assemblage which outcrop at Slate Hill, near the town of Marcellus, New York State. The Marcellus Formation was noted to overlie the Onondaga Limestone (Hall 1839) and to be overlain in turn by shales of the Hamilton Group (Vanuxem, 1840). Currently, the Marcellus Formation of New York State is considered to be a unit within the Hamilton Group and has, itself, been subdivided into the Union Springs, Cherry Valley, and Oatka Creek Members (Cooper 1930; Rickard 1984).

Early Canadian workers failed to identify the Marcellus Formation in Ontario. It was not until Stauffer (1912) noted the presence of a dark shale overlying the Onondaga Limestone (now Dundee Formation), in petroleum exploration wells drilled in Norfolk and Elgin Counties, that the occurrence of the Marcellus Formation in southwestern Ontario was first suspected. Stauffer (1915) also was the first to report black shale fragments washed up on the Lake Erie shore near Port Stanley. The occurrence of outcrops of the Marcellus Formation below lake level was suggested.

In his 1915 description of the Marcellus Formation, Stauffer included strata that subsequently have been assigned to the overlying Bell Formation. He also suggested that outcrops of apparent black shales in the Selkirk-Cheapside area (part of the present Regional Municipality of Haldimand-Norfolk) were referable to the Marcellus Formation. These are now known to be weathered bituminous limestones of the Dundee Formation (Telford and Tarrant 1975a).

More recent publications dealing with the Devonian strata of southwestern Ontario (e.g. Caley 1945; Sanford and Brady 1955; Sanford 1968; Uyeno et al. 1982) usually contain only brief mention of the Marcellus Formation. Clearly, this reflects the fact that the Marcellus is not exposed in the province. The only in-depth study of the unit to date was by Musial (1984).

Correlation of the Marcellus Formation as defined in New York State with the Marcellus Formation as commonly used in southwestern Ontario is a contentious issue. Recent publications by Rickard (e.g. 1984) suggest that the Marcellus Formation of New York State is correlative with the Bell, Rockport Quarry, and Arkona Formations of the Hamilton Group in southwestern Ontario. An implication of this interpretation is that the black shales overlying the Dundee Formation in the Port Stanley area are merely a minor lower part of the Bell Formation. Also, in order for the correlation scheme to "fit", Rickard (1984) invoked a major disconformity between the Arkona Formation and overlying

Hungry Hollow Formation. This interpretation is quite different from the Devonian stratigraphic scheme described by Uyeno et al. (1982) and it has been challenged by Sparling (1985).

Resolution of these stratigraphic issues was beyond the scope of this oil shale resource evaluation of the Marcellus Formation. The nomenclatural system adopted for the present work is that of Uyeno et al. (1982). However, it is hoped that the fundamental data generated by the Oil Shale Assessment Project can be used in future studies to establish precise correlations between Ontario's Devonian sequence and those of neighbouring New York, Ohio and Michigan.

3.3 Distribution

Accurate delineation of the geographic limits of the Marcellus Formation in southwestern Ontario is difficult, especially because of the absence of outcrops and the paucity of reliable drillcore. As noted earlier, the most abundant data useful for distribution and thickness interpretations are the results of downhole geophysical logging in petroleum exploration wells.

Peak or increased values which identify organic-rich beds of the Marcellus Formation are displayed in gamma ray, neutron, density and, to some extent, focussed electric logs. Only the gamma ray and neutron logs are commonly run in petroleum exploration wells drilled in Lake Erie and onshore areas of southwestern Ontario. Of these, the gamma ray log is the most common and it has been used in the distributional analysis of the Marcellus Formation.

In Figure 9, a typical gamma ray log for the Marcellus Formation (from drillhole M-6, see Fig. 8) is compared with a log from a drillhole located well beyond the apparent subcrop limits of the Marcellus (OGS-82-2 Chatham, Johnson et al. 1985). The M-6 log displays three peak responses (ranging up to 150 API units) which correspond with black organic-rich beds. The integrated drillhole log for M-6 in Appendix 2 illustrates this lithological-geophysical relationship.

In the M-6 hole two of the organic-rich beds lie within the Marcellus Formation and one seems to be part of the overlying Bell Formation. Other lithological parameters, as described in Chapter 3.5, have been used to discriminate Marcellus from Bell in southwestern Ontario. Total organic carbon values for the organic-rich beds are listed in Table 5 and are also shown on the M-6 integrated drillhole log in Appendix 2. As illustrated in Fig. 9 and Appendix 2, limestone beds and non-organic shale beds in the Marcellus Formation give very similar log responses.

Organic-rich shale beds typical of the Marcellus Formation were not observed in the Chatham (OGS 82-2) drillhole (Johnson et al. 1985). This is confirmed by the gamma ray log which does not contain the characteristic peaks as shown in the M-6 log. The slight peak at the base of the Bell Formation in the Chatham log may reflect bituminous

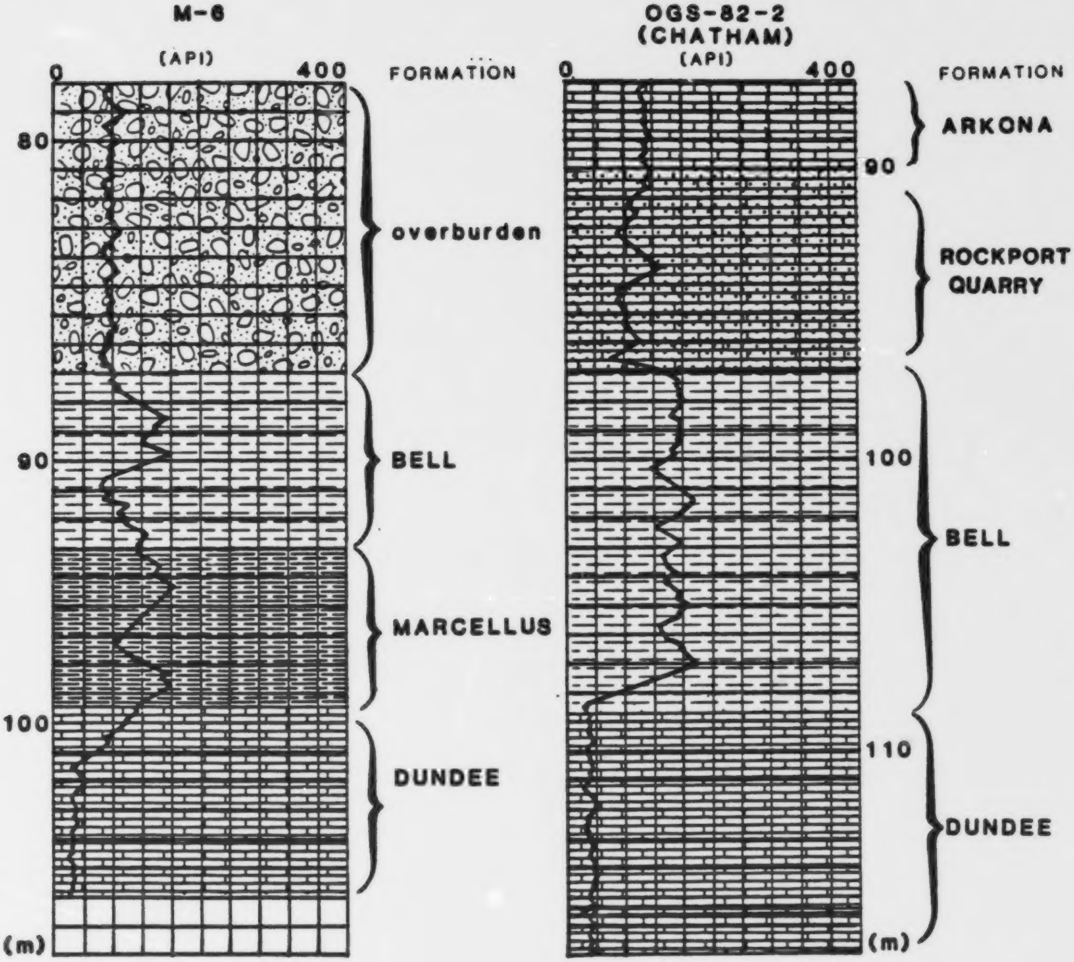


Fig. 9. Comparative gamma ray logs for OGS drill holes M6 and 82-2 (drillholes with and without Marcellus Formation).

TABLE 5. Organic Geochemical data for the Marcellus Formation and adjacent units

M-5	Interval	Depth From (m)	To	Analysis #	TOTAL ORGANIC CARBON %
Bell Formation	Undifferentiated	96.03	96.23	1053	0.9
	"	99.95	100.14	1054	4.4
	"	102.48	102.75	1291	2.6
	"	103.78	104.38	1292	2.3
	"	105.76	105.97	1055	0.6
	"	106.14	106.51	1293	0.5
	"	106.61	107.02	1294	0.6
	"	107.27	107.67	1295	0.5
Marcellus Formation	Upper Organic	108.61	108.82	1056	11.4
	Carbonate	109.26	109.80	1296	1.2
	Carbonate	109.80	110.25	1297	0.5
	Lower Organic	111.00	111.19	1057	4.3
M-6					
Bell Formation	Undifferentiated	88.22	88.42	1059	2.76
	"	88.58	88.95	1298	2.3
	"	89.06	89.41	1299	1.9
	"	90.17	90.53	1300	0.8
	"	91.00	91.37	1301	0.3
	"	91.49	91.73	1060	0.5
	"	92.10	92.43	1302	0.6
	"	93.28	93.62	1303	0.5
Marcellus Formation	Upper Organic	93.64	93.86	1061	9.8
	Upper Shale	94.12	94.17	1304	0.8
	Carbonate	94.60	95.02	1305	0.5
	Lower Organic	96.01	96.20	1062	4.3
M-8					
Marcellus Formation	Upper Shale	84.25	84.47	1064	1.9
	" "	84.51	84.76	1526	1.4
	" "	84.76	85.00	1527	0.8
	Carbonate	85.00	85.25	1528	0.2
	"	85.25	85.50	1529	0.2
	Lower Shale	85.50	85.75	1530	0.2
	" "	85.75	86.00	1531	0.3
	" "	86.00	86.25	1532	0.4
	" "	86.25	86.50	1533	0.3
	Lower Organic	86.50	86.74	1534	2.4
	" "	86.76	86.96	1065	4.5
	" "	86.96	87.21	1535	2.8
	" "	87.21	87.50	1536	3.1
Dundee Formation	Undifferentiated	87.50	87.75	1537	1.3
	"	87.75	87.89	1538	0.2
	Organic Interbed	87.89	88.09	1066	5.3
	Undifferentiated	88.09	88.25	1539	1.3

TABLE 5. Organic Geochemical Data for the Marcellus Formation and adjacent units (Cont'd)

M-8	Interval	Depth (m) From	Depth (m) To	Analysis #	Total Organic Carbon %
Dundee Formation	Undifferentiated	88.25	88.50	1540	1.2
	"	88.50	88.75	1541	0.7
	"	88.75	89.00	1542	0.1
	"	89.00	89.25	1543	0.1
	"	89.25	89.50	1544	0.1
	"	89.50	89.75	1545	0.3
	"	89.75	90.00	1546	0.1
	"	89.75	90.00	1546	0.1
O.G.S.-82-3					
Bell Formation	Undifferentiated	79.7			0.57
	"	85.77			1.49
	"	90.21			0.16
Marcellus Formation	Upper Organic	93.40			5.96
	" "	93.57			3.86
	Carbonate	93.74			0.07
	Lower Organic	94.00			7.38
Dundee Formation	Undifferentiated	97.08			0.45
	Organic Interbed	98.04			3.79
	Undifferentiated	100.40			0.47

hydrocarbons which tend to be concentrated at that geological contact.

The gamma ray log response of the Marcellus Formation does show some variation. In some wells a single peak is evident; more commonly there are two peaks and rarely there are three. Figure 10 shows a typical transition of gamma ray log responses between three adjacent drillholes. Note how the two peaks which define the Marcellus in block #121(A) evolve into a single peak in block #124(D). Throughout this analysis the upper peak, as shown in Figure 10, is the most consistently developed. Where core samples were available for geochemical analysis, the beds which produced the upper peak also have higher total organic carbon (TOC) values (see Appendix 2) than beds represented by the lower peak.

The only regional trend recognized in this distributional analysis of gamma ray logs was the tendency for the peak responses to have a blunt or squared-off appearance in logs from western wells and a more spiked appearance in logs from eastern wells (Fig. 11). This may be the result of more sharply contrasted lithological variations in the eastern subcrop area where carbonate and inorganic shale beds are thicker and more abundant.

The geographic limit of the Marcellus Formation is defined by the zero contour on the isopach map (Back Pocket). On-shore it follows an irregular pattern, subparallel to the shore line, and extends between Ridgetown, St. Thomas and the base of Long Point. This boundary follows the pattern used by

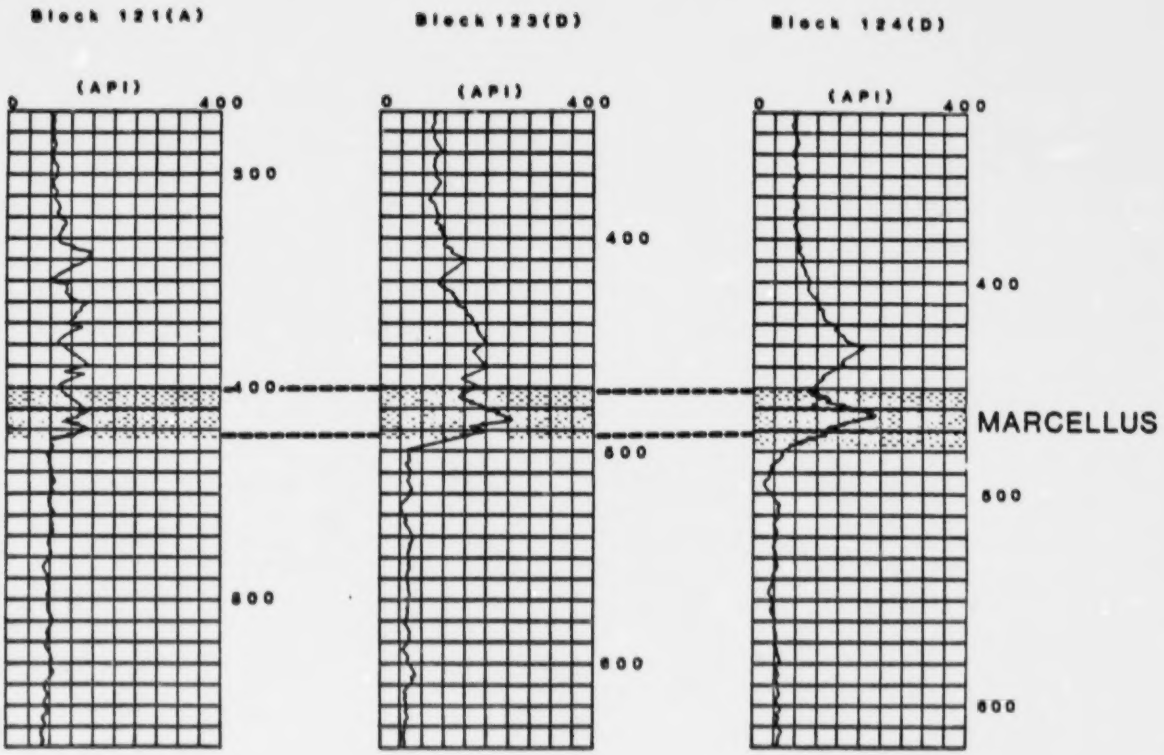


Fig. 10. Evolution of gamma ray log between adjacent drill-holes in Lake Erie; east to west section, note change from two Marcellus peaks into one.
Hole Locations:
-Block 121(A) = Lat. 42-29-48, Long. 80-45-38
-Block 123(D) = Lat. 42-29-53, Long. 80-38-21
-Block 124(D) = Lat. 42-29-54, Long. 80-33-20.

MARCELLUS UNITS	M-5		M-6		M-8		OGS-82-3	
	Thickness M	T.O.C. %	Thickness m	T.O.C. %	Thickness m	T.O.C. %	Thickness m	T.O.C. %
Upper Organic (A)	0.41	11.4	0.50	9.8	eroded	N/A	1.15	4.91
Upper Shale (B)	0.5	N/A	0.41	0.8	eroded* (0.8)	1.37	1.67	N/A
Carbonate (C)	1.1	0.85	1.1	0.5	0.7	0.2	1.68	0.07
Lower Shale (D)	1.05	N/A	0.4	N/A	1.16	0.3	0.75	N/A
Lower Organic (E)	0.25	4.3	0.75	4.3	0.68	3.2	0.15	7.38

Note: N/A indicates no analyses made.
* as this unit is incomplete it is not used in average determinations.

TABLE 6. Thickness and average total organic carbon (TOC) values for Marcellus units in O.G.S. Drillcores.

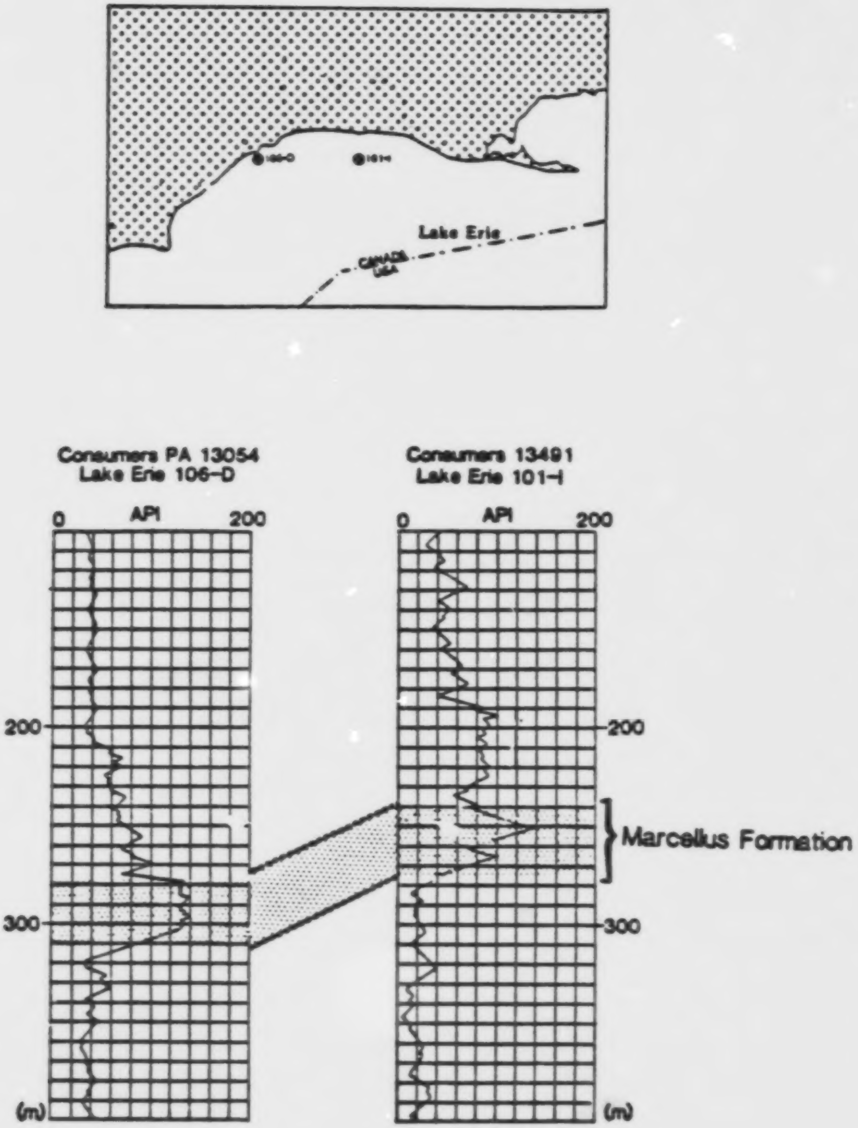


Fig. 11. Comparison of gamma ray log responses in wells from eastern and western subsurface areas.

Sanford (1969b), but has been adjusted to allow for the results of the OGS drilling (e.g. Marcellus absent in holes M-7 and M-9). The gamma ray log for drillhole 109 (see Appendix 3 for complete well identification), 5 km south of Port Dover, provides evidence that the Marcellus underlies much of Long Point. The presence of Marcellus under Long Point Bay is further supported by the logs from drill holes #110 and 111 (see Appendix 3). This is a modification of the Sanford boundary in this area, which parallels and runs to the south of Long Point. The precise eastern limit of the Marcellus is not known as unfortunately, well control in the area is very poor. The absence of a typical Marcellus gamma ray peak in well #114 (see Appendix 3), located to the south of Long Point, suggests termination of the unit in this vicinity.

Similarly, the western boundary is also poorly defined. The drillhole to the west of Ridgetown (#11) indicates 6.0 metres of Marcellus close to the shore line, although Sanford's (1969b) map shows Hamilton Group, or Dundee Formation and no Marcellus Formation in areas north and west of Ridgetown. South of Erie Beach are two wells (#109 and #110) with no apparent Marcellus, suggesting that the unit terminates immediately east of them.

As exploration drilling is prohibited on the United States side of Lake Erie, drilling information for the map stops very abruptly at the Canada-U.S. border.

3.4 Thickness

In addition to helping delineate the extent of the Marcellus Formation in southwestern Ontario, the gamma ray log analysis was also used to determine patterns of regional and local thickness variations and to produce the accompanying isopach map (Back Pocket). One hundred and ten selected petroleum exploration wells were located on an approximate one per block[1] spacing in order to develop the regional picture. A more concentrated group of wells also was examined in three blocks (220, 183, 157 - see isopach map, Back Pocket) to examine the potential for local thickness variations of the unit. The gamma ray logs from the petroleum exploration wells supplemented the limited data available by direct thickness measurements from the six OGS on-shore drillholes.

On the gamma ray logs the base of the Marcellus Formation was placed at the base of the first (lowest) peak indicating a black organic shale bed. Normally this peak has a value of about 150 API units. Below this point the log response decreases markedly in intensity to about 50 API units, representing the limestones of the underlying Dundee Formation. The top of the Marcellus Formation was placed at the top of the second (or rarely third) peak apparently produced by a black organic shale bed. Reliable placement of the upper contact often proved to be difficult as the log signature commonly displayed different shapes, even between adjacent wells (see Fig. 10). The variety of hole diameters, casing programs, grouting procedures, and logging equipment probably account for much of the log variation. Geological parameters are only a minor factor in this regard. Nevertheless, caution should be exercised in using the interpretation of the upper boundary of the Marcellus provided herein.

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[1] one "block" covers approximately 70 km^2.

As illustrated on the accompanying isopach map (Back Pocket), the Marcellus Formation in southwestern Ontario and beneath north-central Lake Erie occurs as a series of elongate ridges which trend approximately parallel to the regional strike (east-northeast to west-southwest). Length of the subcrop pattern is about 175 km, with a width of about 40 km. Regional dip in the area is directly into the Appalachian Basin at approximately 3 m/km (Musial 1982).

The northern subcrop edge of the unit is sub-parallel to the trend of the Algonquin Arch. Whether this reflects erosion of strata which formerly draped over the Arch, or stratigraphic pinch-out of the Marcellus against the Arch, is uncertain.

Determining the style of eastern and western termination of the ridges of the Marcellus is hampered by a lack of suitable drillholes or gamma ray log records in these areas.

Southward thickening of the Marcellus from its subcrop edge is variable. Between drillholes 9 and 10 (see isopach map) the unit thickens from 0 to 5 m over a distance of 4 km. However, between drillholes 109 and 110 near Long Point Bay (see isopach map), the unit thickens by only 1.5 m over a distance of 18 km.

The thickest section of Marcellus Formation recorded in this study was 12 m (measured in Consumers Gas drillhole 13628 Lake Erie 182-A-isopach map hole #73). The thinnest complete section of the unit was 0.5 m noted in Consumers Gas drillhole 13337 Lake Erie 182-L-isopach map hole #83). Both of these holes lie in the central part of the offshore area that was examined. Surprisingly these holes are located only 3 km apart. The average thickness calculated from the drill holes used in this study was 5.1 m.

3.5 Lithology

The following detailed lithological description for the Marcellus Formation is based upon the examination of cores from the OGS drillholes (Fig. 8, Table 4). Review of the gamma-ray logs from these drillholes and petroleum exploration wells through the subcrop area of the Marcellus Formation suggest that these descriptions of the OGS cores reflect the apparent overall pattern of lithological units. Variations that do occur are mainly related to relative thickness differences of individual units (see previous section).

In the OGS drillholes which intersect strata assignable to the Marcellus Formation, the same basic lithological elements were present in each hole. In descending order these are:

Unit A - Upper organic shale
B - Upper shale (non-organic)
C - Carbonate
D - Lower shale (non-organic)
E - Lower organic shale.

This sequence of elements is clearly evident in drillholes M-5, M-6 and M-8, and to a lesser degree in OGS-82-3. In the latter, the upper organic shale (A) is not very dark and the lower organic shale (E) is very thin to the extent that it is not evident in the gamma-ray logs. Had direct core examination not been possible, recognition of Marcellus in this drillhole would have been uncertain.

Dundee-Marcellus Contact

Underlying the Marcellus Formation are limestones of the Dundee Formation. These are buff to grey-brown, fine to coarsely crystalline (in part granular) richly fossiliferous limestones. The fossil material present within this formation is largely broken brachiopod and crinoidal debris. Shaly partings are common. Also present are vugs, some of which exhibit oil staining.

Within the uppermost metre of the Dundee, there is one and sometimes two distinct interbeds of organic shale, similar to the basal shales of the Marcellus. The interbeds are 1 to 10 cm thick and usually occur 10 to 15 cm below the base of the Marcellus. The organic shale interbed (in the Dundee) encountered in drillhole OGS-82-3 had a TOC content of 3.8%. Immediately beneath the interbeds are 0.5 cm thick horizons of concentrated bioclastic debris. These suggest that a minor break occurred in deposition between each cycle of carbonate and shale. The upper contacts of the organic shale interbeds are sharp.

Unit E - Lower Organic Shale

This is the lowest Marcellus Formation unit present and is a brownish-black fissile shale. "Although it appears to be the darker coloured of the two organic shale units present (A, E), it has the lower average TOC content (4.14% compared with 7.38%, see Table 5)". A brownish hue noted on some bedding planes in unit E results from concentrations of flattened amber coloured spore cases. Apart from this microfossil material, the unit is poorly fossiliferous.

This interval has an average thickness of 0.45 m, varying between 0.15 m in OGS-82-3 and 0.68 m in M-8 (see Table 6). From the correlation of the OGS drillholes, (Fig. 12), this unit appears to thicken in the central part of the subcrop area underlying land. The upper contact of unit (E) is gradational with the overlying Lower Shale (unit D).

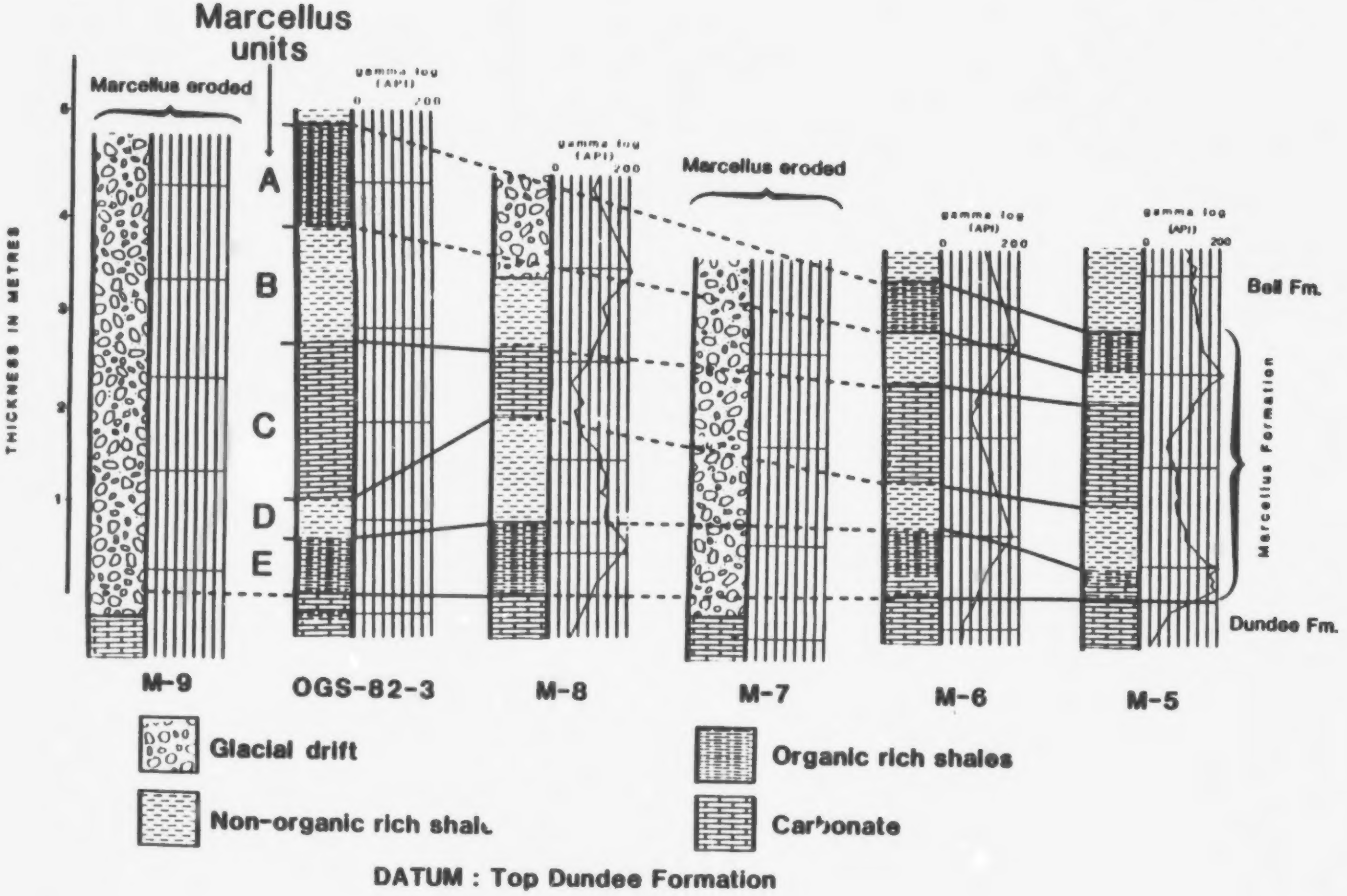
Marcellus units
Marcellus eroded
THICKNESS IN METRES
1
2
3
4
5
A
B
C
D
E
gamma log (API)
0
200
Marcellus eroded
Bell Fm.
Marcellus Formation
Dundee Fm.
M-9
OGS-82-3
M-8
M-7
M-6
M-5
Glacial drift
Non-organic rich shale
Organic rich shales
Carbonate
DATUM : Top Dundee Formation

Fig. 12. Cross section of OGS cored holes through the Marcellus Formation.

Unit D - Lower Shale (non-organic)

The Lower Shale is a blue-gray silty and partly calcareous shale. It is very fissile and can be rich in complete articulated shells and shell debris of various brachiopod taxa. This unit is differentiated from unit E (organic-rich shale) by the change in colour, increase in faunal content and increased fissility. Strata of unit D cannot be differentiated from the blue-grey shales of the Bell Formation, overlying the Marcellus. This unit (D) has an average thickness in the OGS cores of 0.84 m (see Table 6, Fig. 12) with an average TOC content of only 0.3% (see Table 5 for range of values).

Strata of the Lower Shale are gradationally overlain by carbonate rocks of unit C.

Unit C - Carbonate

This unit is composed of buff to blue-grey very fine to medium grained impure limestone. These strata are richly fossiliferous in echinoderm and brachiopod debris. They are dense and free of vugs or visible pore spaces. No stylolites were detected in this unit, and the rock does not display fissility. The average TOC values for this unit was found to be 0.38% (see Table 5) with an average thickness in the OGS holes of 1.14 m. Significant changes in thickness are evident between adjacent holes for both this unit and the underlying unit (D), as evident in the drillhole cross-section (e.g. between OGS-82-3 and M-8, Fig. 12). Rocks of the unit (C) carbonate are gradationally overlain by shales of unit (B).

Unit B - Upper Shale (non-organic)

The Upper Shale is a blue-grey, silty and partly calcareous shale. This unit is very similar to the lower shale unit (D), but tends to have a lower fossil content. Again, like unit (D), the fossil assemblage present is mostly articulated brachiopod shells and shell debris, and the unit is highly fissile. Mean thickness from the OGS drillholes for this unit is 0.86 m (see Table 6) with the cross-section (Fig. 12) suggesting an overall westward thickening. The average TOC value for this interval is 1.17% (see Table 5), much higher than is present in unit (D), but again too low to be considered an oil shale. This unit is gradationally overlain (although this contact is sharper than the previously mentioned contacts) by the organic shales of unit A.

Unit A - Upper Organic Shale

The Upper Organic Shale, is composed of brown-black or dark-grey to black, moderately fissile shale. This interval tends to be lighter coloured than the Lower Organic Shale (unit E), but has a much higher average TOC value of 7.38%

(see Table 5). The average thickness for this interval, in the OGS cored holes amounted to 0.68 metres, with the trends shown in the cross-section (Fig. 12) suggesting a westward thickening. Overall, when reviewing the geophysical gamma-ray logs for the non-OGS holes used, it appears the upper organic shale (A) is the most predominant, in terms of both magnitude and consistency. The upper contact of the Upper Organic Shale is used to denote the upper contact of the Marcellus Formation.

Marcellus-Bell Contact

Throughout most of its Ontario subcrop area, the Marcellus Formation is overlain by rocks of the Bell Formation; the basal unit of the Hamilton Group. Where not overlain by the Bell, the Marcellus directly underlies glacial cover. The Bell/Marcellus contact is present in OGS drillholes M-5, M-6 and OGS-82-3. The Bell Formation consists of blue-grey, silty, fossiliferous shales, lithologically similar to the upper and lower shale units (B and D) present in the Marcellus. The contact between the upper organic shale (A) (i.e. top of the Marcellus) and Bell Formation is sharp but is devoid of scour, rill and other features indicative of extended erosion.

In each of the OGS cores which intersected Bell Formation strata (M-5, M-6, OGS-82-3), there are thin (up to 20 cm thick) organic rich beds in the lower part of the Bell Formation. These have sharp upper and lower contacts and are lighter in colour than the upper organic shale (A) of the Marcellus, but they are a distinctly darker colour than the surrounding Bell strata. TOC analyses were made of the Bell organic interbed encountered in OGS-82-3 and it was found to have a TOC content of 4.4%. Many of the off-shore exploration wells used in this study display gamma-ray logs suggesting the presence of thin organic rich interbeds in the Bell Formation. This was supported by the presence of darker coloured chips in the appropriate cutting samples. Including these interbeds in the Marcellus Formation was discounted due to their thinness and discontinuous nature.

3.6 Stratigraphic Relationships

Knowledge of Middle Devonian black shales of the eastern United States has been increased considerably through the activities of the Eastern Gas Shales Project (Roen 1984; see Chapter. 2.3). Black shale units equivalent to the Marcellus Formation of Ontario are present over a broad part of the Appalachian Basin extending from New York State through Pennsylvania, eastern Ohio, West Virginia and into Maryland, Virginia and Kentucky (Fig. 6).

The basic stratigraphic sequences of these black shales and associated units in the immediately adjacent States of New York, Pennsylvania, and Ohio are very similar to the Marcellus sequence in Ontario. This suggests that a much higher degree of correlation is possible with these areas than has previously been achieved. To the south and southeast of these states, the Middle Devonian sequences contains a greater proportion of clastic units and the black organic shales and non-organic grey shales are not as distinctly differentiated. The Marcellus Formation of Ontario apparently lies at the distal edge of the Appalachian Basin Middle Devonian black shale province.

New York. As presently defined (Van Tyne and Peterson, 1978; Rickard, 1975, 1984), the Marcellus Formation of New York directly overlies an eroded carbonate platform (Onondaga Formation; see Table 7) and is the basal unit of the Hamilton Group. The remaining overlying formations of the Hamilton Group (Skaneateles, Ludlowville, Moscow) are mainly blue-grey shales with minor black organic shales and carbonate horizons. The Middle Devonian sequence of western New York is capped by the Tully Limestone. An equivalent to this unit has not been recognized in Ontario (Uyeno et al. 1982).

As noted previously, the Marcellus in New York is divided into three members - the Union Springs (black organic shale), Cherry Valley (limestone), and the thicker Oatka Creek (black organic shale). These three members are easily identified on downhole gamma ray logs (Rickard, 1984) and they present a geophysical signature very similar to that of the Marcellus Formation in Ontario . The Cherry Valley and Oatka Creek Members are present throughout the New York subcrop area but

<table>
<tr><th>ONTARIO
(UYENO et al 1982)</th><th colspan="3">NEW YORK
(RICKARD, 1984)</th><th colspan="3">PENNSYLVANIA
(SCHWIETERING, 1977)</th><th colspan="2">OHIO
(SCHWIETERING, 1977)</th><th colspan="2">WEST VIRGINIA
(SCHWIETERING, NEAL & DOWSE, 1978)</th><th colspan="3">VIRGINIA
(HASSON & DENNISON) 1978)</th></tr>
<tr><td>NO EQUIVALENT UNIT</td><td colspan="3">TULLY LST</td><td colspan="3">TULLY LST</td><td colspan="2">UPPER PART OLENTANGY</td><td>TULLY LST</td><td>BURKET OR HARRELL</td><td colspan="3">HARRELL SHALE</td></tr>
<tr><td rowspan="3">HAMILTON Gp</td><td rowspan="6">HAMILTON Gp</td><td colspan="2">MOSCOW</td><td rowspan="6">HAMILTON Gp</td><td colspan="2" rowspan="3">MAHANTANGO</td><td rowspan="6">LOWER PART OLENTANGY</td><td rowspan="3">PROUT</td><td rowspan="6">HAMILTON Gp</td><td rowspan="3">UPPER ZONE</td><td rowspan="6">MILLBORO SHALE</td><td rowspan="3">MAHANTANGO INFLUENCE</td><td rowspan="3"></td></tr>
<tr><td colspan="2">LUDLOWVILLE</td></tr>
<tr><td colspan="2">SKANEATELES</td></tr>
<tr><td rowspan="3">MARCELLUS Fm</td><td rowspan="3">MARCELLUS</td><td>OATKA CREEK mb</td><td rowspan="3">MARCELLUS</td><td></td><td rowspan="3">PLUM BROOK Fm</td><td rowspan="3">LOWER ZONE</td><td rowspan="3">MARCELLUS INFLUENCE</td><td></td></tr>
<tr><td>CHERRY VALLEY mb</td><td>PURCELL</td><td>PURCELL mb</td></tr>
<tr><td>UNION SPRINGS mb</td><td></td><td></td></tr>
<tr><td>DUNDEE Fm</td><td colspan="3">ONONDAGA Fm</td><td colspan="3">ONONDAGA Fm</td><td colspan="2">ONONDAGA Fm (DELAWARE)</td><td>ONONDAGA Fm</td><td>NEEDMORE SHALE</td><td colspan="3">NEEDMORE SHALE</td></tr>
</table>

Table 7 - Lithostratigraphic Correlation of the Marcellus Formation.

the Union Springs shale appears to pinch-out on the western side of the state (Rickard, 1984).

The most obvious difference between the Marcellus in New York and Ontario is thickness. In Chemung and Chautauqua Counties of western New York the formation is up to 30 m thick as compared to the average of 5.1 m in Ontario.

Pennsylvania. Strata named the Marcellus Formation underlie all of northeastern and western Pennsylvania (Fig. 6). They are also included in the Hamilton Group and are overlain by the Mahantango Formation (Harper and Piostroski 1978; Schwietering, 1977). A facies relationship is suggested between the two formations as the Marcellus thins to the northwest, out of the Appalachian Basin, while the Mahantango thickens in this direction (Harper and Poistroski 1978). However there is still a net reduction in total thickness of the Hamilton Group to the northwest.

The stratigraphic sequence is very similar to that in New York and Ontario with Marcellus shales overlying an eroded carbonate surface and being overlain in turn by a thick sequence of shales and minor limestone intervals. A carbonate unit within the Marcellus of Pennsylvania is called the Purcell Limestone; it is correlative with the Cherry Valley Member of the Marcellus in New York and is probably equivalent to the carbonate interval (Unit C) of the Marcellus in Ontario.

Harper and Piostroski (1978) reported thicknesses of up to 75 m for the Marcellus in western Pennsylvania. They indicated an average thickness of 20 m with the unit thinning to zero near Lake Erie. Their distribution map shows the Marcellus occurring as a series of elongate ridges parallel to regional strike of the beds. As described previously (Chapt. 3.3), the Marcellus in Ontario exhibits a similar distribution pattern.

Ohio. Strata equivalent to the Marcellus Formation are confined to the eastern side of Ohio by the Findlay and Cincinatti Arches. These basement ridges extend north-south through western Ohio forming a barrier between the Appalachian Basin in the east and the Michigan and Illinois Basins to the west. This is similar to the role of the Algonquin Arch between the Michigan and Appalachian Basins. The presence in Ohio of a dark shale facies overlying Middle Devonian carbonates and being equivalent to the Marcellus in New York was first noted by Lafferty (1941). However, knowledge of these shales is not as advanced as in the neighbouring states.

The dark shale facies is referred to the lower part of the Olentangy Shale (Table 7) and has been described as black organic rich shales with interbedded limestone and organic poor shales (Schwietering 1979). Correlation of the limestone intervals with the Cherry Valley and Purcell limestones has not been confirmed. Lafferty (1941) suggested a thickness of up to 60 m for the "lower part of the Olentangy" but stratigraphic sections in Grey et al. (1982) showed a more modest 12 m. The published thicknesses are probably a function of what was defined as black shale.

West Virginia. In West Virginia, strata termed the "Lower zone of the Hamilton Group" have been correlated with the Marcellus in Pennsylvania and New York (Schwietering et al. 1978). Thicknesses exceed 75 m but the unit thins rapidly to the west. Over much of the state, these strata are divisible on the basis of downhole gamma-ray logs into three zones - upper and lower zones of high gamma-ray values separated by an interval of low gamma-ray readings. The middle interval probably correlates with the Cherry Valley and Purcell Limestones and Unit C of the Marcellus in Ontario.

In West Virginia, the "upper zone of the Hamilton Group", which has been correlated with the Mahantango Formation of Pennsylvania, contains shales of much darker colour than in neighbouring areas.

Virginia. Strata equivalent to the Marcellus Formation are referred, in Virginia, to the lower part of the Millboro Shale. They have also been termed the Marcellus Influence (Schwietering et al. 1978) in reference to the dark colour and high gamma-ray values of the shales. In eastern West Virginia and adjacent Virginia, strata of the Marcellus Influence overlie the Needmore Shale, a calcareous shale that is age equivalent to the Onondaga Formation of New York (Telford 1979, p.203). Hasson and Dennison (1978) identified a carbonate unit which they termed the Purcell Member within the Marcellus Influence at the type section of the Millboro Shale.

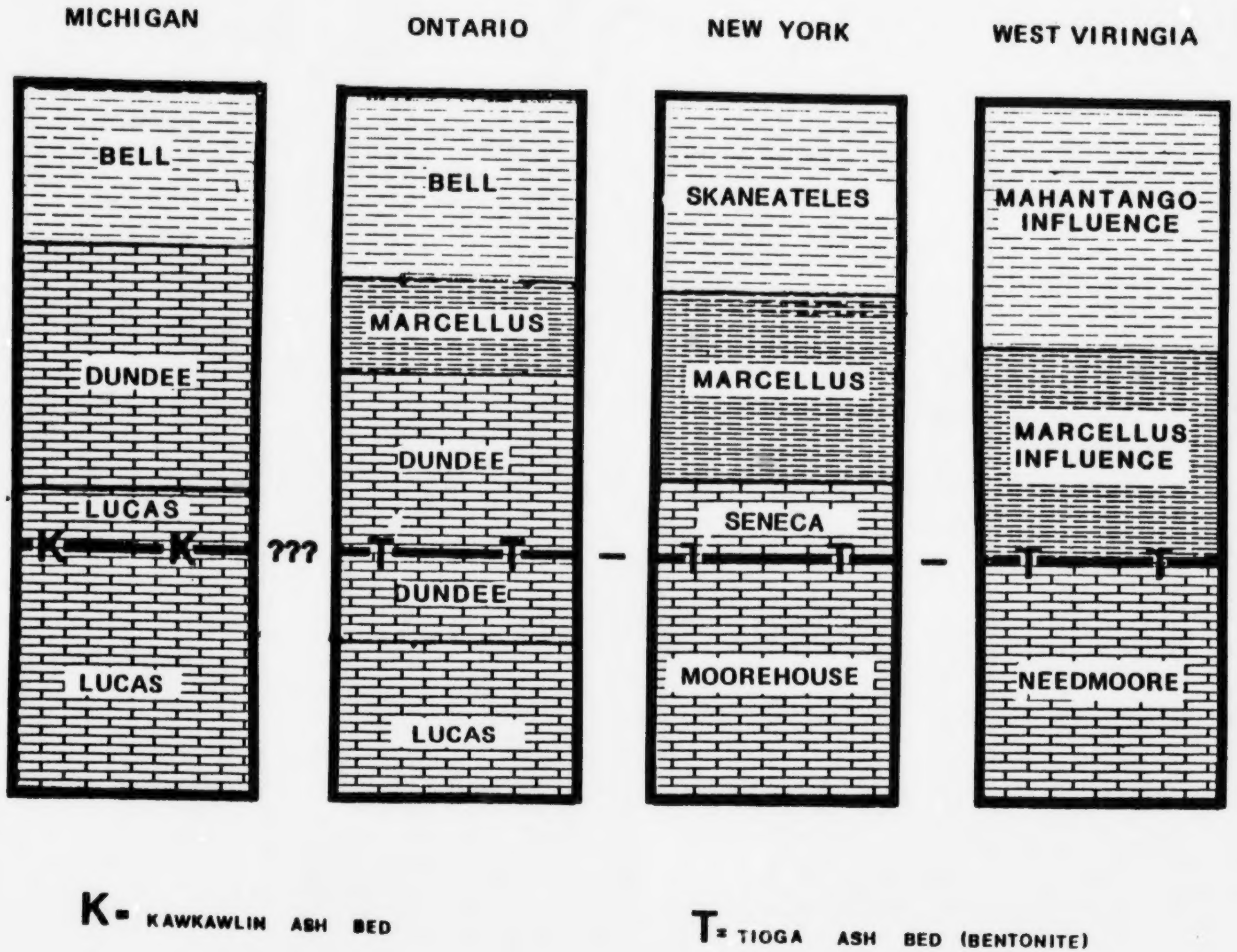
MICHIGAN
ONTARIO
NEW YORK
WEST VIRINGIA
BELL
DUNDEE
LUCAS
K
K
LUCAS
???
BELL
MARCELLUS
DUNDEE
T
T
DUNDEE
LUCAS
SKANEATELES
MARCELLUS
SENECA
MOOREHOUSE
MAHANTANGO INFLUENCE
MARCELLUS INFLUENCE
NEEDMOORE
K= KAWKAWLIN ASH BED
T= TIOGA ASH BED (BENTONITE)

Fig. 13. Distribution of the Middle Devonian black organic shale facies in the Appalachian Basin.

Here the Marcellus Influence was 120 m in thickness with the Purcell Member 15 m thick.

Dennison and Naegele (1978) have also recognized strata equivalent to the Marcellus in nearby western Maryland.

Diachroneity of Marcellus. The Marcellus Formation (and its equivalents) in the Appalachian Basin is diachronous, with the base of the unit becoming younger to the northwest. This is confirmed by the relative stratigraphic position of the base of the Marcellus to the Tioga Ash Bed.

The Tioga Ash Bed (formerly termed Tioga Bentonite - see Roen and Hosterman 1982) is a volcanic ash layer which forms a consistent time marker horizon throughout the eastern and northeastern parts of the Appalachian Basin. It has also been recognized in the Illinois and Michigan Basins (e.g. Droste and Vitaliano, 1973; Baltrusaitis 1974). The Tioga marks the top of the Middle Devonian Onesquethaw Stage (Dennison and Textoris, 1977). There are actually several Tioga tuffaceous layers with a combined total thickness in Virginia of up to 61 m (Dennison and Textoris, 1977). However, it is the Tioga middle coarse zone which has the widest distribution and is most commonly used as a time marker.

In Virginia, West Virginia and southern Pennsylvania, the black shales of the Marcellus Formation or its equivalent directly overlie the Tioga middle coarse zone. However, farther north in western New York, the Marcellus is separated from the Tioga by limestones of the Seneca Member of the Onondaga Formation. In Ohio, the Tioga is thought to lie within the Delaware Formation, stratigraphically below the Marcellus. Sanford (1968) tentatively recognized the Tioga within the Dundee Formation of the southwestern Ontario, significantly below the base of the Marcellus (Fig. 13).

In Michigan, the Kawkawlin Bentonite of Baltrusaitis (1974) has been tentatively correlated with the Tioga and it lies stratigraphically lower, within the Lucas Formation of the Detroit River Group (Fig. 13).

3.7 Depositional Relationships

The depositional setting and regional sedimentation patterns of the Middle Devonian black shales in the Appalachian Basin have been reviewed by numerous authors. For recent summaries see Janka and Dennison (1980) and Roen (1984). The following discussion pertains specifically to the Marcellus Formation as observed in southwestern Ontario and immediately adjacent areas.

The relatively sharp lower contact of the Marcellus Formation observed in the OGS drillholes suggests that deposition of the unit began on an eroded surface. A very similar relationship occurs at the Dundee Formation-Bell Formation contact as observed in drillhole OGS 82-2 Chatham (Johnson et al. 1985), where the Marcellus Formation is absent due to subsequent erosion or nondeposition.

The sequence of lithologies and gradational boundaries between the lithological units within the Marcellus Formation suggests that the depositional environment alternated gradually between well oxygenated and poorly oxygenated conditions. The black organic shales and the limestone units represent extreme conditions of weak and strong oxygenation respectively with the non-organic grey shales indicating a transitional environment.

By inference, oil shales are formed in an oxygen deficient environment. This is required to inhibit the development of scavenging bacteria and other higher order biota which would otherwise devour and oxidize organic material that was being deposited. Deep water is not needed to produce the oxygen deficient conditions required for oil shale deposition, as much as a lack of effective oxygen circulation. There is no lithologic evidence in the Marcellus strata to suggest deep water deposition.

No megafossils were observed in the organic-rich shale units of the Marcellus Formation. Insoluble residue analysis of these shales produced a very sparse microfauna of ostracods, scolecodonts, conodonts, tentaculitids and small gastropods together with some spore cases. The non-organic shales of the Marcellus Formation contain a more abundant and diverse fauna, including abundant shell material. Underlying limestones of the Dundee Formation and overlying shales of the Bell Formation contain very rich mega- and micro-faunas.

The depositional history of the Marcellus Formation and subadjacent and superadjacent formations in southwestern

Ontario can be interpreted briefly as follows. Limestones of the Dundee Formation were deposited in well oxygenated conditions. The appearance of thin black shale interbeds in the upper part of the Dundee Formation indicates periods of oxygen-starved conditions also existed during deposition of that unit. Following deposition of the Dundee, there was a brief hiatus as suggested by the peneplaned surface and fossil debris sheets associated with the lower contact. Clastic deposition began during a major period of oxygen-starved conditions which resulted in deposition of the lower organic shale of the Marcellus Formation. The carbonate and non-organic grey shales of the middle part of the Marcellus Formation, with a fauna including filter-feeding organisms, indicate that better oxygenated conditions returned to the depositional area. Eventually the environment again became oxygen-starved and deposition of the upper organic shale took place. Finally, well oxygenated conditions again returned, reflected by the fossiliferous grey shales of the Bell Formation.

The depositional conditions interpreted for the Marcellus Formation in southwestern Ontario are probably closely analogous to the conditions which produced the Middle Devonian black shales and associated units throughout the Appalachian Basin. As described in the previous section (Chapt. 3.6) the sequence of lithologies in the Ontario Marcellus (basically shale-carbonate-shale) is very similar to correlative sequences in western New York (Rickard, 1984), Pennsylvania (Schwietering, 1977), Virginia (Hasson and Dennison (1978), and elsewhere. The principal difference is the scale of the sequences which range from over 120 m thickness in Virginia to only about 5 m in Ontario. This is clearly related to the locations of the sequences within the sedimentary basin and the effects of varying proximity to terrigenous source areas and varying tectonic and subsidence patterns on shelf and basin areas.

4. GEOCHEMISTRY

4.1 Inorganic

Inorganic geochemical analyses were conducted by the OGS Geoscience Laboratories on twenty-eight samples from the Bell (12), Marcellus (12), and Dundee (4) Formations. The major constituents were reported as oxides (Table 8).

Analyses were carried out firstly by x-ray fluorescence (XRF), using both fused bead and pressed powder pellets. The initial analyses showed that samples with intermediate SiO_2 levels (20-35%) and CaO levels of 20 to 45% could not be totalled accurately to 100%. This resulted partly from a lack of suitable standards needed for the calibration of instruments. The samples were subsequently analyzed using wet chemistry (i.e. gravimetrically). These tests indicated that the original levels for SiO_2 were reasonably accurate, but that CaO was analyzing 7 to 8% lower by the XRF method. Thus the CaO values presented here were determined using wet chemistry, and the remaining values were determined by XRF. It is possible that the organics in the matrix of the sample were depressing the XRF derived CaO values (C. Riddle - OGS pers. comm.).

The major constituent results are shown in Table 8, and have been subdivided by formation and lithology. Average values are also calculated. It is clearly evident from

Formation	Lithology	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	CO_2	S	L.O.I	Total*
Bell Fm.	Organic-Poor Shale	40.9	14.6	3.99	2.03	14.7	0.28	3.54	0.40	0.05	0.04	12.5	0.75	18.3	98.8
"	"	51.0	17.4	4.54	2.22	6.93	0.20	4.57	0.51	0.00	0.04	8.48	0.51	11.5	99.0
"	"	48.9	15.6	3.83	2.19	10.4	4.30	4.16	0.42	0.00	0.03	12.9	0.59	14.2	99.5
"	"	46.9	14.9	4.90	1.99	11.1	0.29	4.19	0.46	0.03	0.03	10.6	1.75	15.0	99.7
"	"	52.0	19.0	6.24	2.26	2.11	0.36	4.66	0.58	0.04	0.03	17.1	1.29	12.1	99.4
"	"	41.7	14.0	3.29	1.78	14.0	0.31	3.39	0.35	0.04	0.03	19.6	0.86	18.9	99.3
"	Average	46.8	15.9	4.55	2.09	10.04	0.28	4.09	0.45	0.03	0.03	14.4	0.96	15.0	99.3
"	Limestone	26.0	8.80	2.47	1.50	30.9	0.24	3.29	0.42	0.00	0.03	25.4	0.36	26.6	100.3
"	"	16.7	5.43	1.30	1.48	38.4	0.15	1.30	0.16	0.06	0.05	32.5	0.22	33.1	98.1
"	"	20.5	6.86	2.00	1.91	36.3	0.24	1.72	0.17	0.01	0.07	28.8	0.49	29.6	98.5
"	"	25.9	8.42	2.22	1.40	31.3	0.19	2.26	0.17	0.02	0.05	26.3	0.81	26.8	98.7
"	"	18.9	6.12	1.92	2.36	36.6	0.26	1.73	0.15	0.01	0.06	29.1	0.70	30.4	97.5
"	"	21.3	8.21	1.91	1.29	33.7	0.39	1.66	0.16	0.24	0.04	28.7	0.45	28.6	97.5
"	Average	21.6	7.31	1.97	1.47	39.5	0.25	2.08	0.21	0.06	0.05	28.5	0.51	29.2	98.4
Marcellus Fm.	Organic-Poor Shale	50.7	18.9	5.32	2.19	6.56	0.09	4.50	0.71	0.03	0.06	6.56	0.42	10.9	100.0
" "	"	28.6	10.3	1.90	1.74	28.2	0.30	2.38	0.22	0.08	0.09	25.5	0.38	25.1	98.9
	Average	39.7	14.6	3.61	1.97	17.4	0.20	3.44	0.47	0.06	0.05	16.03	0.40	18.0	99.5
" "	Organic-Rich Shale	47.9	16.2	5.00	2.49	5.97	0.19	4.44	0.65	0.04	0.03	22.8	1.41	15.5	98.4
" "	"	48.5	17.0	4.55	2.99	6.10	0.20	4.58	0.67	0.13	0.03	20.6	0.93	14.9	99.1
" "	"	47.5	17.2	4.78	2.32	7.32	0.08	4.58	0.67	0.14	0.03	19.6	1.10	15.1	99.8
" "	"	46.4	17.4	3.80	2.54	4.89	0.18	4.86	0.53	0.00	0.03	10.2	0.95	14.3	99.9
" "	"	41.8	14.5	3.33	1.93	16.0	0.17	3.49	0.33	0.01	0.04	15.4	0.78	18.1	99.7
" "	"	47.8	17.9	5.00	2.39	7.62	0.15	4.36	0.67	0.06	0.06	12.4	0.73	13.8	99.8
" "	"	48.8	16.7	4.71	2.09	3.55	0.31	4.26	0.62	0.05	0.03	34.6	1.34	19.6	98.9
" "	"	42.4	15.1	4.52	2.25	11.2	0.24	4.08	0.56	0.06	0.03	22.1	1.59	18.8	99.2
" "	"	41.2	16.1	4.20	2.38	11.2	0.26	4.15	0.51	0.11	0.03	20.8	1.73	18.5	99.1
	Average	45.8	16.5	4.49	2.31	9.0	0.20	4.31	0.58	0.07	0.03	19.8	1.17	16.3	99.3
" "	Limestone	23.9	7.41	2.10	1.92	32.5	0.20	1.84	0.19	0.00	0.06	28.3	0.58	27.9	98.1
Dundee Fm.	Limestone	1.69	0.99	0.33	0.32	55.5	0.12	0.11	0.01	0.07	0.03	41.4	0.16	41.2	99.8
" "	"	2.28	0.60	0.25	0.60	54.6	0.14	0.15	0.01	0.11	0.03	40.4	0.06	41.1	99.8
" "	"	2.85	1.04	0.31	1.39	51.6	0.10	0.19	0.01	0.06	0.03	39.8	0.17	40.7	98.3
" "	"	3.06	1.05	0.32	0.92	51.1	0.09	0.23	0.02	0.13	0.03	40.2	0.25	90.0	99.0
	Average	2.45	0.92	0.31	0.80	53.2	0.11	0.17	0.01	0.09	0.03	40.45	0.16	40.75	99.22

* Totals do not include CO_2 and S.

TABLE 8. MAJOR ELEMENTS IN THE BELL, MARCELLUS AND DUNDEE FORMATIONS compiled from samples representative of the units in all OGS cores (reported as oxides %).

these few samples, that both organic and inorganic shales of the Marcellus and Bell Formations are highly siliceous.

The other constituents are typical in terms of abundances, with the limestone intervals appropriately higher in CaO and lower in SiO2. Due to the small data set, standard deviation calculations were not made, however it does appear that the range for the organic-rich beds is much narrower than is shown by the organic-poor intervals. This suggests, that the environment for organic-rich shale deposition was much more restrictive, in terms of the range of inorganic material both added to and generated by the system, than was the case for deposition of the non-organic shales.

Although no trace element analyses were conducted on samples of the Marcellus Formation for this study, Brown (1985) reported trace elements data for chip samples of the Marcellus (and enclosing strata?) from oil and gas exploration wells below Lake Erie and southern Ontario. A summary of Brown's major and trace element data, representing 22 samples from 10 wells, is presented in Table 9.

Organic-rich shales are typically enriched in a number of trace elements, including Cu, Pb, Zn, Ni, Co, Cr and V (Vine and Tourtelot 1970), however the Marcellus data (Table%2% 9) more closely approximates average (i.e. non-organic-rich) shale composition (eg. Turekian and Wedepohl 1961; Wedepohl 1969). The non-enriched nature of the Marcellus trace

Table 9 - Major and trace element data from chip samples of Marcellus (and enclosing?) strata (from Brown 1985). Major elements reported in oxide weight percent and trace elements in 'ppm', except where otherwise noted (N.D. not detected).

	Average	Maximum	Minimum
Major Elements			
SiO_2	39.17	52.71	24.23
Al_2O_3	13.08	17.80	7.93
Fe_2O_3	4.42	8.64	2.35
MgO	1.99	2.28	1.42
CaO	17.14	31.11	2.66
Na_2O	0.14	0.28	0.03
K_2O	3.47	5.01	2.13
TiO_2	0.49	0.69	0.34
P_2O_5	0.11	0.26	0.07
MnO	0.04	0.11	0.03
LOI	18.77	27.02	10.10
Trace Elements			
Nb	19.6	36.5	5.6
Zr	100.2	135.7	74.9
Y	45.7	80.2	20.9
Sr	254.6	328.0	156.8
Rb	142.6	196.4	81.4
Pb	30.1	49.6	16.7
Zn	70.3	155.3	7.8
Cu	14.5	22.7	10.4
Ni	19.9	63.3	8.4
Co	9.8	28.0	N.D.
Cr	37.0	48.4	20.7
Ba	299.1	437.9	122.5
V	83.8	143.8	44.1
S(%)	2.4	3.0	0.5
Ga	23.2	38.5	7.3

element data and a comparison of Brown's (1985) major element data with the data in Table 8 suggests that his chip samples represent homogenized organic-poor and organic-rich Marcellus intervals and possibly intervals of enclosing strata. This also illustrates the thin nature of the organic-rich beds in the Marcellus and the potential for dilution problems in their extraction.

4.2 Organic

Samples selected from three of the six Marcellus Formation drill cores and from well-cuttings of nineteen exploration wells drilled beneath Lake Erie were analyzed, for organic carbon content and yield on pyrolysis. Results from cores are reported by Barker (1985) whereas TOC determinations on well cuttings samples are reported in Table 10 with the techniques shown in Appendix 1. These data combined with previous studies (Barker et al. 1983; Powell et al. 1984) which investigated the geochemical nature, origins and maturity of the organic matter in the Marcellus, enables an evaluation of the oil shale potential of this formation.

Thermal maturity. Studies of the sedimentary sequence in southern Ontario (Powell et al. 1984; Legall et al. 1981) conclude that organic matter in the Devonian strata only attained an immature to marginally-mature level of thermal maturity. That is, the indigenous organic matter (i.e.

TABLE 10. Total Organic Carbon (TOC) determinations for well cutting samples of the Marcellus Formation

Well Location		Depth (m)	TOC (weight %)
154 E		167	1.1
		171	1.6
		174	2.1
		177	2.6
		180	1.1
		183	3.0
BL 157 TR D		153	1.5
		162	1.5
		168	2.2
BL 157 TR G		174	2.9
		180	3.4
BL 157 TR R		186	1.7
BL 182 TR R		-	3.7
BL 182 TR R		-	3.4
BL 182 TR X		219	2.6
BL 183 TR G		153	3.3
		195	1.6
		198	2.6
		201	2.6
BL 183 TR R		207	3.4
BL 183 TR S		207	3.0
BL 185 TR T		168	4.5
BL 185 TR A		140	10.6
		165	5.8
		210	2.4
		213	2.3
BL 185 TR D		165	2.2
BL 185 TR H		136	6.8
		171	6.1
BL 220 TR F		245	3.9
BL 220 TR H		232	1.3
BL 220 TR M		250	2.4
BL 220 TR N		220	2.1,2.2
BL 221 TR N	(A)	209	4.2
	(B)	158	1.0
	(C)	156	1.1

kerogen) has not experienced a thermal history sufficient to have generated significant quantities of migratable hydrocarbon (i.e. conventional oil). Barker et al (1983) reported that the temperature-programmed pyrolysis of two Marcellus samples yielded only small peaks attributable to bitumen, suggesting the Marcellus to be only marginally mature. Vitrinite reflectance values for the Marcellus also reported by Barker et al (1983) supported this maturation level.

The organic geochemical studies by Powell et al. (1984) determined that Marcellus Formation samples have a sufficiently high proportion of hydrocarbon of the bitumen type to be considered marginally mature to mature and that the yield of hydrocarbons are sufficient to consider the Marcellus a "good" potential source rock for conventional petroleum generation (see Figure 15 in Powell et al. 1984).

Thus, the Marcellus Formation is consider to have generally attained a marginally-mature level of thermal maturity such that a significant, but small proportion of the organic carbon is present in the form of bitumen with the remainder in the form of kerogen. It is unlikely that a significant portion of the bitumen has been lost by migration processes. Thus, the Marcellus Formation is intermediate in thermal maturity somewhere between Ontario's immature Devonian Kettle Point Formation and the mature Ordovician Collingwood Member.

Geochemistry of the organic matter. Visual assessment of kerogen particles from two samples of the Marcellus by P. Gunther (Petro-Canada) reported in Barker et al. (1983) indicated a dominance of amorphous (possibly algal or bacterial) and exinous (possibly spores and pollen) particles over plant-derived vitrinous and fusinous particles. This assemblage is typical of organic matter from both marine and terrestrial sources deposited in a marine environment. This material typically has a geochemistry of Type II kerogen (Tissot and Welte, 1978) and is similar to the kerogen geochemistry ascribed to the Collingwood and Kettle Point shales.

The relative "richness" of the Marcellus Formation organic matter can be assessed by comparing the pyrolysis yield per unit weight of organic carbon for samples from this formation to that of the other Ontario oil shales. In order to make this comparison among units which are themselves variable, the linear regression expressions relating Fischer Assay pyrolysis yield to the amount of total organic carbon (TOC) are used to predict the FA yields for hypothetical samples having 10% TOC. The regression equations parameters and the predicted pyrolysis yields are shown in Table 11.

TABLE 11. Regression equation parameters and predicted Fischer Assay yield for hypothetical samples with 10% TOC.

FA = a TOC + b

	Regression Eq. a	Parameters b	Hypothetical FA (1/tonne)
Kettle Point Formation	5.26	-4.08	48.5
Marcellus Formation	5.74	+0.412	57.8
Collingwood Member (Lindsay Fm.)	7.52	-11.7	63.5

The TOC/FA relationships in Table 11 indicates that relative to the other Ontario oil shales the Marcellus Formation yields an intermediate amount of oil. The Hytort pyrolysis (a technique in which hydrogen is added to the retorting process) of Collingwood and Kettle Point samples always result in higher yields than the Fischer Assay (no hydrogen added), indicating that hydrogen, not carbon limits pyrolysis yield and that the organic "richness" of these samples really relates to the amount of hydrogen contained in its organic matter. This observation, combined with the relatively lower yields per unit of organic carbon of the Marcellus Formation (Table 11) suggests that the Marcellus Formation organic matter is somewhat hydrogen-poor with respect to the Collingwood Member oil shales.

The somewhat hydrogen-poor nature of the Marcellus Formation organic matter could result from the incorporation of either less hydrogen-rich, type I material or more hydrogen-poor, terrestrial, type III material. Visual assessment (Barker et al. 1983) points to a slightly greater proportion of terrestrial-derived vitrinous and fusinous material in the organic matter as the cause of its "leanness" relative to the Collingwood oil shales.

Conclusions. The Marcellus Formation contains a significant thickness of organic rich (greater than 1% TOC) shale. The organic matter is dominantly kerogen, but up to 15% could be bitumen produced by thermal cracking of the kerogen at the marginally-mature thermal maturation level attained by this shale. The kerogen is probably geochemically type II, but less-hydrogen-rich than the Collingwood Member oil shale. This geochemical difference probably reflects a greater proportion of terrestrially-derived type III (geochemically) kerogen in the Marcellus Shale.

5. RESOURCE EVALUATION

Two types of resource estimates were prepared for the Marcellus Formation. The first, termed Land Accessible Resource Estimate, is based largely on information or interpretations from the four OGS drillholes which intersected the formation. The premise for this estimate is that any resource development of the Marcellus would most likely be in the area where the overburden is thinnest and the unit is most accessible (i.e. on land).

However, the Marcellus Formation also extends beneath Lake Erie and, although data from this subcrop area is not as reliable, this information was combined with the OGS drillhole data to produce the second estimate, termed the Total Canadian Formation Estimate.

Both estimates have severe limitations. The Land Accessible Resource Estimate is based on a small data set and should be regarded with caution. At best, this evaluation should only be viewed as a general guide.

South of the OGS drillhole pattern, beneath Lake Erie, the Marcellus is apparently thicker and underlies a large area. However, the unit can be identified only by its geophysical log signature and the presence of dark shale cuttings in some petroleum exploration wells. Thus, both the location and very nature of the formation becomes very speculative, making the Total Canadian Formation Estimate somewhat arbitrary.

5.1 Land Accessible Resource Estimate

Although probably more reliable than the Total Canadian Formation Estimate that follows, this estimate is based on a minimal amount of data, hence is considered only a reasonable estimate of what may be present, and not what is present.

Geochemical data used in this resource evaluation of the Marcellus Formation are shown in Tables 5 and 12. Clearly identifiable are the relatively high Total Organic Carbon (TOC) values which distinguish the upper and lower organic rich beds. These are also noted in the integrated drill hole logs (Appendix 2), and have been discussed previously, see Section 3.3.

Also evident from Table 5 is that, apart from the upper and lower organic beds, all the intervening strata appears to have an average T.O.C. content of less than 2.5%. As this is the normal cut-off point for an oil shale to be of economic interest (or indeed to be an oil shale by definition - see Section 1.2 and Macauley, 1985), these low grade strata have not been included in this evaluation. Thus, this estimate only includes the organic rich beds.

Shown in Table 12 are the results of Fischer Assays and Rock-Eval Analyses of the OGS core samples (carried out by the Institute of Sedimentary and Petroleum Geology in Calgary). Fischer Assay is an oil shale industry standard which suggests the oil recovery that may be achieved using a simple retorting process. Rock-Eval Analysis provides a range of information

					Fischer Assay Analyses				Rock-Eval Analyses			
	Sample Interval m	T.O.C.	Density from Logs	Oil-Specific Gravity	Yield- Oil l/t	Yield- Oil l/M^3	Yield- Water l/t	Ratio-l/t to % TOC oil	Yield l/t	Yield l/m3	Yield kg/t	Ratio-l/t to %TOC oil
DRILL HOLE - M5												
Upper Organic Bed	108.6-108.8	11.4	2.38	.915	64.2	153.0	5.0	5.63				
	108.6-108.8	12.63										
	108.6-108.8	12.59							97.9	372	89.6	7.74
									90.6	210.6	82.9	7.19
Lower Organic Bed	111.0-111.19	4.3	2.40	.903	22.9	55.0	9.7	5.33				
	111.35											
	111.3								38.1	90.4	34.4	7.72
									37.7	89.5	34.0	6.65
DRILL HOLE - M6												
Upper Organic Bed	93.64-93.86	9.8	2.37	.903	59.2	140.3	6.7	6.04				
	93.6	10.58										
	93.0	10.49							81.3	192.7	73.42	7.7
									77.7	184.1	70.23	7.4
Lower Organic Bed	96.1-96.2	4.3	2.39	.907	29.6	70.7	5.8	6.87				
	96.34	4.84										
	96.34	4.97							37.2	88.9	33.8	7.69
									37.7	90.1	34.23	7.59
DRILL HOLE - M8												
Lower Organic Bed	88.76-86.96	4.5	2.39	-	20.4	48.8	13.3	4.53				
	86.96-87.21	2.8										
	87.21-87.50	3.1										

TABLE 12 - Marcellus Formation - Fischer Assay and Rock-Eval Analyses

(S1, S2, Tmax, etc.) including total yield estimate that is similar to, but higher than the Fischer Assay Values (for details of both tests - see Appendix 1).

Rock density values are needed for any resource estimate. As the Marcellus Formation contains at least three lithologies (carbonate, normal shale and oil shale), any density estimate for the unit tends to be something of an average. As actual density measurements for the rock samples were not made, the density values were taken from logs run from the boreholes (see Johnson 1985).

Using the above mentioned data, this estimate considers only the part of the Marcellus Formation which lies below land, or is below Lake Erie within 1 kilometre of the shoreline. The on-shore subcrop pattern for the unit is based on the map of Uyeno et al. (1982) with some modification to allow for the new data from the OGS cores. Because of the scatter of data points (wells) and the difficulty in defining the Marcellus Formation in the subsurface, the proposed subcrop distribution of the unit remains tentative.

North of Lake Erie, the Marcellus underlies about 440 square kilometres of Ontario; a further 35 square kilometres of subcrop area lies beneath Lake Erie within 1 kilometre of the shoreline. Therefore, the total land accessible Marcellus amounts to about 475 square kilometres. To the west, the Marcellus Formation is overlain by units of the Hamilton Group, and is not considered as accessible to resource extraction and therefore is not included in this estimate.

As there are two organic rich zones in the Marcellus, separate resource estimates are made for each zone as follows. These values are then combined for the Land Accessible Formation Estimate. Drill core M-8 did not intersect an upper organic zone, although the gamma ray peak locations on the geophysical logs suggest it is present. Its absence, in M-8, is probably a result of core recovery problems, more than an absence of the upper organic bed, thus it has been included in this calculation. As both the upper and lower organic rich beds were intersected by several drillholes, values for organic rich bed thickness and yield were averaged from data in Tables 5 and 6.

	av. density	av. thickness (m.)	Yield (l/t)
Upper Organic	2.37	0.68	61.7
Lower Organic	2.39	0.45	24.3

(Individual values for each hole are shown in Table 5 and 6).

The calculations for a reserve value for each organic bed were calculated using the following equation:

Surface area (m2) x zone thickness (m) x rock density x yield (l/tonne)/1000 = Reserve in cubic metres of oil (equivalent kerogen)

The calculations are as follows:

Upper Organic

$475 \times 1000 \times 1000 \times 0.68 \times 2.37 \times 61.7/1000 = 4.7 \times 10^7$

Lower Organic

$475 \times 1000 \times 1000 \times 0.45 \times 2.39 \times 24.3/1000 = 1.2 \times 10^7$

Thus the total land accessible Marcellus Formation resource amounts to 5.9×10^7 cubic metres or approximately 3.7×10^8 barrels.

From the limited data, some interpretation can be made of the kerogen distribution within the land accessible portion of the formation. From Table 12, it is evident that the relationship (ratios) between T.O.C. content and yield (as per Rock-Eval data) is fairly constant and is sufficient to use T.O.C. as a predictor of yield. As the drillholes align in an approximate east to west line (M-5, M-6, M-8, OGS-82-3) an east-west trend in kerogen richness is suggested. For the upper zone, kerogen content increases to the east (T.O.C.%: M-5= 11.4, M-6 = 9.8, OGS-82-3 = 4.9).
Unit thickness for the upper zone increases to the west (thickness (m): M-5 = 0.41, M-6 =0.50, M-8 (estimated from gamma ray logs) =0.7, M-9 = 1.15). For the lower organic-rich zone, the kerogen content appears to increase to the west (T.O.C.%: M-5 = 4.3, M-6 = 4.3, M-8 =3.5, OGS-82-3 = 7.3%) while the zone thickens to the east, up to M-5 where it thins again (M-5 = 0.25, M-6 = 0.75, M-8 =0.68, OGS-82-3 = 0.15).

Thus, according to the OGS core data, there appears to be an inverse relationship between kerogen richness and unit thickness for both organic rich zones. Whether this relationship applies to the substantially thicker off-shore Marcellus is not known.

5.2 Total Canadian Formation Evaluation

An estimate can be made of the kerogen (oil equivalent) content of the Marcellus Formation which is present below land and below the Canadian part of Lake Erie. Two basic assumptions have been made which appear to be supported by the geophysical logs. Firstly, the two main organic beds present on land are also found below Lake Erie and, secondly, as the formation appears to thicken (to over 12 metres), the relative proportion of the unit which is organic rich remains constant. Although the precise shape of the subcrop/subsurface distribution pattern for the Marcellus remains uncertain, it appears to be lensoidal with a length of at least 175 km and a width of 75 km. Using the total formation isopach map (back pocket) for thickness, it is suggested that the total Canadian portion of the formation amounts to 3.25 x 1010 cubic metres of strata.

Using data from the complete land cores as a guide (M-5, M-6 and OGS-82-3, Table 6), it appears the two organic rich beds average 27% of the total formation, thus 9.0×10^9 m^3 of the formation is organic rich. Averaging Fischer Assay and density values from Table 12, give an average yield of 43.5 litres per tonne and a density of 2.38. Applying this to the total organic rich volume above, using the previous equation, suggests that the unit may contain 9.31×10^8 m^3 or 5.8×10^9 barrels of oil (kerogen equivalent).

5.3 Development Considerations

Although the above figures for both the Land Accessible Formation Estimate (3.7 x 108 barrels) and Total Canadian Formation Estimate (5.8 x 109 barrels) are very large and even assuming an oil price much higher than at present (1986), development potential of the unit is probably limited. Drift cover over the unit, even in the most accessible on-shore area, is at least 86 metres. This, combined with a unit thickness of only a couple of metres, suggests stripping ratios of 50:1. This and other environmental factors clearly precludes a strip mining operation. Furthermore, the organic-rich beds are separated by beds of organic poor material necessitating a more complex high grading process. As the beds are often less than 0.5 metres thick, selective underground mining of the individual organic rich zones would be difficult and expensive based on existing technology.

In addition, the nearby Upper Devonian Kettle Point Formation oil shale (Russell 1985) and Upper Ordovician Collingwood Member oil shale (Russell and Telford 1983) are of greater thickness, underlie much larger areas, and can be found under thinner overburden cover, making them more attractive alternatives.

6. REFERENCES

Baltrusaitis, E.J.
1974: Middle Devonian bentonites in the Michigan Basin; American Association of Petroleum Geologists Bulletin, Vol. 58, p.1323-1330.

Barker, J.F.
1985: Geochemical analysis of Ontario oil shales; Ontario Geological Survey, Open File Report 5568, 77pp.

Barker, J.F., and Chatten, S.
1982: A technique for determining low concentrations of total carbonate in geological materials; Chemical Geology, Vol. 36, p.317-323.

Barker, J.F., Dickhout, R.D., Russell, D.J., Johnson, M.D. and Gunther, P.
1983: Paleozoic black shales of Ontario - possible oil shales; in Miknis, E.P. and McKay, J.F. (editors), Geochemistry and Chemistry of Oil Shales, American Chemical Society Symposium Series No.230, American Chemical Society, p.119-138.

Barnes, C.R., Norford, B.S., and Skevington, D.
1981: The Ordovician system in Canada: correlation chart and explanatory notes; Paris, International Union of Geological Sciences, 27p.

Beards, R.J.
1967: Guide to subsurface Paleozoic stratigraphy of southern Ontario; Ontario Department of Energy and Resources Management, Paper 67-2.

Bolton, T.E.
1957: Silurian stratigraphy and paleontology of the Niagara Escarpment in Ontario; Geological Survey of Canada, Memoir 289, 145p., with maps.

Brown, G.
1985: Comparative geochemistry of southwestern Ontario black shales, in Bedrock and Till Clasts, for Glacier Provenance; Unpublished Bachelor of Science Thesis, University of Western Ontario, 143p.

Caley, F.J.
1945: Paleozoic Geology of the Windsor-Sarnia Area, Ontario; Canada Department of Mines and Resources, Geological Survey, Memoir 240, 4 maps, 277p.

Church, P.L.
1984: Geology and geochemistry of the Collingwood Member,Lindsay Formation, southern Ontario; Unpubl. B.Sc.Thesis, University of Waterloo, 40p.

Churcher, P.L., and Dickhout, R.D.
1987: Analysis of ancient sediments for total organic carbon- a new method; Journal of Geochemical Exploration, Vol. 29, p.235-246.

Cooper, G.A.
1930: Stratigraphy of the Hamilton Group of New York; Parts 1 and 2; American Journal of Science, Vol. 19, p.116-134, 214-236.

Delitala, F.A.
1984: The Mineralogy and Geochemistry of the Kettle Point Oil Shale, Southwestern Ontario; Unpublished Master of Science Thesis, University of Western Ontario, 194p.

Dennison, D.M.
1976: Appalachian Queenston delta related the eustatic sea level drops accompanying Late Ordovician glaciation centered in Africa in Basset, M.G. (ed.). The Ordovician System, University of Wales Press, Cardif, p.107-120.

Dennison, J.M. and Textoris, D.A.
1977: Tioga Bentonite Time-Marker associated with Devonian shales in Appalachian Basin in Schott, G.L., Overbey, W.K. Jr., Hunt, A.E. and Komar, C.A. eds., Eastern Gas Shales Symposium 1st Proceedings: U.S. Dept. of Energy, Special Paper MERC/SP-775, p.166-182.

Dennison, J.M. and Naegele, O.D.
1978: Tioga Bentonite time marker associated with Devonian shales in Appalachian Basin; in Schott,%2% G.L., Overbey, W.K., Jr., Hunt, A.E., and Komar, C.A. (editors) of Eastern Gas Shales Symposium, 1st Proceedings, United States Department of Energy, Special Paper MERC/SP-77/5, p.166-182.

Droste, J.B. and Vitaliano, C.J.
1973: Tioga Bentonite (Middle Devonian) of Indiana; Clay sand Clay Minerals Bulletin, Vol. 21, p.9-13.

Dusseault, M.B. and Loftsson, M.
1985: The mechanical properties of the Kettle Point oil shales; Ontario Geological Survey, Open File Report 5560, 93p.

Ells, G.D.
1978: Stratigraphic cross sections extending from Devonian Antrim Shale to Mississippian Sunbury Shale in the Michigan Basin; United States Department of Energy, Report No. FE-2346-30.

Espitalie, J., Laporte, J.L., Madec, M., Masquis, F., Laplat, P., and Boute, V.A.
1977: Methode rapide de caracterisation des roches meres, de Leaur Potential petrolier et de leur degre d'evolution; Rev. Inst. Fr. Petrolieo., Vol. 32, p.23-42.

Ferrigno, K.F.
1971: Environmental influences on the distribution and abundance of conodonts from the Dundee Limestone (Devonian), St. Marys, Ontario; Canadian Journal of Earth Sciences, Vol. 8, p.378-386.

Grey, J.P., Hodges, D.A., and Knapp, N.F.
1982: An integrated study of the Devonian age black shales in eastern Ohio; Ohio Department of Natural Resources, Division of Geological Survey, Report for Contract D.E. AS21-76ET12131, 174p.

Hall, J.
1939: Third Annual Report to the 4th Geologic District of the State of New York; New York Geological Survey Annual Report 3, p.287-339.

Harper, J.A. and Piotrowski, R.G.
1978: Stratigraphy, extent, gas production, and future gas potential of the Devonian organic rich shales in Pennsylvania; United States Department of Energy, Second Eastern Gas Shale Symposium, Vol.1, p.310-329.

Harris, D.
1985: Graphic logs of oil shale intervals - Ordovician Collingwood Member and the Devonian Kettle Point and Marcellus Formation; Ontario Geological Survey, Open File Report 5527, 222p.

Hasson, K.O. and Dennison, J.M.
1978: Devonian Harrell and Millboro Shales in parts of Pennsylvania, Maryland, West Virginia, and Virginia; in Schoot, G.L., Overbey, W.K., Jr., Hunt, A.E., and Komer, C.A. (editors) for: Eastern Gas Shale Symposium, 1st Proceedings, United States Department of Energy, Special Paper MERC/SP-77/5, p.634-642.

Hubbard, A.B.
1965: Automated modified Fischer Assay retorts for assaying oil shale and bituminous materials; United States Department of the Interior, Bureau of Mines Report of Investigations 6676, 19p.

Janka, J.C. and Dennison, J.M.
1980: Devonian oil shale; in Symposium Papers: Synthetic fuels from oil shales; Chicago Institute of Gas Technology, p.21-116.

Johnson, M.D.
1982: Oil Shale Assessment Project; p.135-138 in Summary of Field Work, 1982, by the Ontario Geological Survey, edited by J. Wood, O.L. White, R.B. Barlow, and A.C. Colvine, Ontaric Geological Survey, Miscellaneous Paper 106, 235p.

Johnson, M.D.
1983: Oil Shale Assessment Project, deep drilling results 1982-1983, Toronto Region; Ontario Geological Survey, Open File Report 5477, 17p.

1985: Oil Shale Assessment Project, shallow drilling results, 1982-1983, Kettle Point and Marcellus Formations; Ontario Geological Survey, Open File Report 5531, 1 figure, 2 maps, numerous lithological and geological logs in back pocket, 44p.

Johnson, M.D., and Telford, P.G.
1985: Paleozoic Geology of the Kagawong area, District of Manitoulin (41G/16); Ontario Geological Survey, Preliminary Map 2669, scale 1:50 000, Geology 1979-1981.

Johnson, M.D., Russell, D.J., and Telford, P.G.
1983a: Oil Shale Assessment Project, Volume 1, shallow drilling results 1981-1982; Ontario Geological Survey, Open File Report 5458, 36p.

1983b: Oil Shale Assessment Project, Volume 2, drill holes for regional correlation 1981-1982; Ontario Geological Survey, Open File Report 5459, 20p.

1985: Oil Shale Assessment Project, drillholes for regional correlation 1983-1984; Ontario Geological Survey, Open File Report 5565, 8 figures, 6 drill logs in back pocket, 49p.

Klapper, G., and Philip, G.M.
1971: Devonian conodont apparatuses and their vicarious skeletal elements; Lethaia, Vol. 4, p.429-452.

Lafferty, R.C.
1941: Central basin of Appalachian geosyncline; American Association of Petroleum Geologists, Bulletin, Vol. 25, p.781-825.

Larter, S.R., and Douglas, A.G.
1978: Low-molecular weight aromatic hydrocarbons in coal maceral pyrolysates as indicators of diagenesis and organic matter type in "Environment Bio-chemistry and Geomicrobiology", Krumbein, W.E. (ed.), Ann Arbor Science, p.373-386.

Legall, F.D., Barnes, C.R., and Macqueen, R.W.
1981: Thermal maturation, burial history and hot spot development, Paleozoic strata of southern Ontario-Quebec, from conodont and acritarch colour alteration studies; Bulletin of Canadian Petroleum Geology, v.29, p.492-539.

Lilienthal, R.T.
1978: Stratigraphic cross sections of the Michigan Basin; Michigan Department of Natural Resources, Geological Survey Division, Report of Investigations 19, 36p., 89 sections.

Liberty, B.A.
1969: Paleozoic geology of the Lake Simcoe area, Ontario; Geological Survey of Canada, Memoir 355, 201p.

Lomenick, T.E.
1983: Regional geologic assessment of the Devonian-Mississippian shale sequence of the Appalachian, Illinois, and Michigan Basins relative to potential storage/disposal of radioactive wastes; Oak Ridges National Lab, 145p.

Macauley, G.
1984: Geology of the oil shale deposits of Canada; Geological Survey of Canada, Paper 81-25, 65p.

Macauley, G., Snowdon, L.R., and Ball, F.D.
1985: Geochemistry and geological factors governing exploitation of selected Canadian oil shale deposits; Geological Survey of Canada, Paper 85-13, 65p.

Martini, I.P.

1971: Regional analysis of sedimentology of the Medina Formation (Silurian), Ontario and New York; American Association of Petroleum Geologists Bulletin 55, p.1245-1251.

Matthews, R.D.

1983: The Devonian-Mississippian oil shale resource of the eastern United States; 16th Oil Shale Symposium: Institute of Gas Technology, Golden Colorado, p.1-12.

Musial, R.P.

1982: Geology of the Marcellus Formation in southwestern Ontario; Unpublished B.Sc. Thesis, University of Western Ontario, 4 maps, 32p.

Oliver, W.A., Jr.

1976: Noncystimorph colonial rugose corals of the Onesquethaw and lower Cazenovia stages (Lower and Middle Devonian) in New York and adjacent areas; United States Geological Survey, Professional Paper 869.

Powell, T.G., Macqueen, R.W., Barker, J.F., and Bree, D.G.

1984: Geochemical character and origin of Ontario oils; Bulletin of the Canadian Society of Petroleum Geologists, Vol. 32, p.289-312.

Rickard, L.V.

1975: Correlation of the Silurian and Devonian rocks in New York State; New York State map and Chart Series 24, 16p.

1984: Correlation of the subsurface Lower and Middle Devonian of the Lake Erie region; Geological Society of American Bulletin, Vol. 95, p.814-828.

Robl, T.L., and Koppenaal, D.W.

1982: The chemical and engineering properties of eastern oil shales; Institute of Mining and Minerals Research, Lexington, Kentucky, 288p.

Roen, J.B.

1984: Geology of the Devonian black shales of the Appalachian Basin; Organic Geochemistry, Vol. 5, p.241-254.

Roen, J.B., and Hosterman, J.W.
1982: Misuse of the term "bentonite" for ash beds of Devonian age in the Appalachian Basin; Geological Society of America Bulletin, Vol. 93, p.921-925.

Russell, D.J.
1985: Depositional analysis of a black shale using gamma-ray stratigraphy: the Upper Devonian Kettle Point Formation of Ontario; Bulletin of the Canadian Society of Petroleum Geologists, Vol. 33, p.236-253.

Russell, D.J. and Telford, P.G.
1983: Revisions to the stratigraphy of the Upper Ordovician Collingwood beds of Ontario - a potential oil shale; Canadian Journal of Earth Science, Vol. 20, p.1780-1790.

Russell, D.J. and Telford, P.G.
1984a: Stratigraphy and oil shale potential of the Upper Ordovician Collingwood Member in the northeast Michigan Basin; Geological Association of Canada - Mineralogical Association of Canada, Abstracts with Programs, Vol. 9, p.102.

Russell, D.J. and Telford, P.G.
1984b: Geology of the Long Rapids Formation, Moose River Basin; p.117-118 in Summary of Field Work, 1984, Ontario Geological Survey, edited by J. Wood, O.L. White, R.B. Barlow and A.C. Colvine, Ontario Geological Survey, Miscellaneous Paper 119, 309p.

Rybansky, R. and Trevail, R.A.
1983: Oil and Gas Exploration, Drilling and Production Summary, 1982, Ontario Ministry of Natural Resources, Oil and Gas Paper 4, 174p.

Sacheli, A.L.
1985: The geochemistry of the Ordovician Collingwood Member, Lindsay Formation, southern Ontario; University of Western Ontario, London; Unpublished B.Sc. thesis, 50p.

Sanford, B.V.
1961: Subsurface stratigraphy of Ordovician rocks in southwestern Ontario; Geological Survey of Canada, Paper 60-26, 54p.

1968: Devonian of Ontario and Michigan; in Proceedings of the International Symposium on the Devonian System, D.H. Oswald (editor), Alberta Society of Petroleum Geologists, Calgary, Vol. 2, p.973-999.

Sanford, B.V.
1969a: Subsurface studies of the Paleozoic; in Report of Activities, Part A: April to October, 1968, Geological Survey of Canada, Paper 69-1A, p.244.

1969b: Geology, Toronto-Winsdor area, Ontario; Geological Survey of Canada, Map 1263A.

Sanford, B.V., and Brady, W.B.
1955: Paleozoic Geology of the Windsor-Sarnia Area, Ontario; Geological Survey of Canada, Memoir 278, 2 maps, 65p.

Sanford, B.V., and Quillian, R.C.
1959: Subsurface stratigraphy of Upper Cambrian rocks in southwestern Ontario; Ottawa Department of Mines and Technical Surveys, 33p.

Sanford, B.V., Thompson, F.J. and McFall, G.H.
1985: Plate tectonics - a possible controlling mechanism in the development of hydrocarbon traps in southwestern Ontario; Bulletin of the Canadian Society of Petroleum Geologists, Vol. 33, p.52-71.

Scalan, R.S. and Smith, J.E.
1970: An improved measure of the odd-even predominance in the normal alkanes of sediment extracts and petroleum: Geochemica et cosmochemica Acta. Vol. 34, p.611-620.

Schwietering, J.F.
1979: Devonian shales of Ohio and their eastern and southern equivalents; United States Department of Energy CR-79/2, 68p.

Schwietering, J.F., Neal, D.W., and Dowse, M.E.
1978: Tully (?) Limestone and Hamilton Group in north-central and east-central West Virginia; in United States Department of Energy, Second Eastern Gas Shales Symposium Vol.1, p.240-250.

Snowdon, L.R.
1984: A comparison of Rock-Eval pyrolysis and solvent extraction results from the Collingwood and Kettle Point oil shales, Ontario; Bulletin of the Canadian Society of Petroleum Geology, Vol. 32, No. 3, p.327-334.

Sparling, D.R.
1985: Correlation of the subsurface Lower to Middle Devonian of the Lake Erie region: Alternative interpretation and reply; Geological Society of American Bulletin, Vol. 96, p.1213-1220.

Stauffer, C.R.
1915: The Devonian of southwestern Ontario; Geological Department of Mines, Geological Survey Memoir 34, 341p, 1 map.

Stromquist, J.K., Dickhout, R., and Barker, J.F.
1984: Oil Shale Assessment Project; Volume 4, analytical geochemistry of selected Ontario potential oil shales; Ontario Geological Survey, Open File Report 5461, 41p.

Swanson, V.E.
1960: Oil yield and uranium content of black shales; United States Geological Survey Professional Paper 356-A, 44p.

Telford, P.G.
1976: Paleozoic Geology of the Woodstock-Grand Bend area, southern Ontario; in Summary of Fieldwork, 1976 by the Geological Branch, V.G. Milne et al. eds., Ontario Division of Mines, Miscellaneous Paper MP 67, p.156-158.

1978: Silurian stratigraphy of the Niagara Escarpment, Niagara Falls to the Bruce Peninsula, Ontario; Toronto '78 Field Trip Guidebook, edited by A.L. Currie and W.O. Mackasey, Geological Society of America - Geological Association of Canada - Mineralogical Association of Canada, Annual Meeting, p.28-42.

1979: Devonian conodont distribution - provinces or communities?; in Historical Biogeography, Plate tectonics, and the Changing Environment, Gray, J., and Boucot, A.J. (editors), Oregon State University, p.201-213.

Telford, P.G. and Hamblin, A.P.
1980: Paleozoic Geology of the Simcoe Area, Southern Ontario; Ontario Geological Survey, Preliminary Map P.2234, Geology Series, scale 1:50 000, Geology 1975, 1976.

Telford, P.G., and Johnson, M.D.
1984: Paleozoic Geology of Southwestern Ontario; Geological Association of Canada - Mineralogical Association of Canada Field Trip Guidebook #1, 45p.

Telford, P.G. and Tarrant, G.A.
1975a: Paleozoic Geology of the Welland - Fort Erie area, southern Ontario; Ontario Division of Mines, Preliminary Map P.989, Geological Series, scale 1:50 000, Geology 1974.

1975b: Paleozoic geology of Dunnville area, southern Ontario; Ontario Division of Mines, Preliminary Map P.988, Geological Series, scale 1:50 000, Geology 1974.

Telford, P.G., Russell, D.J., and Johnson, M.D.
1984: Paleozoic stratigraphy nomenclature in the Ontario portion of the Michigan Basin; Geological Association of Canada - Mineralogical Association of Canada, Program with Abstracts, Vol. 9, p.110.

Tissot, B., and Welte, D.
1978: Petroleum Formation and occurrence; Springer- Verlag Publishers, Berlin-New York, 538p.

Tuffnell, P., and Ludvigsen, R.
1984: The trilobite Triarthrus in the Whitby Formation (Upper Ordovician) of southern Ontario and a biostratigraphical framework; Ontario Geological Survey, Open File Report 5516, 55p.

Turekian, K.K., Wedepohl, K.H.
1961: Distribution of the elements in some major units of the Earth's crust; Geological Society of America, Bulletin, Vol. 72, p.175-191.

Uyeno, T.T., Telford, P.G., and Sanford, B.V.
1982: Devonian conodonts and stratigraphy of southwestern Ontario; Geological Survey of Canada Bulletin 322, 55p.

VanTyne, A.M. and Peterson, J.C.
1978: Thickness, extent of, and gas occurrence in Upper and Middle Devonian black shales of New York; in United States Department of Energy, Second Eastern Gas Shale Symposium, Vol. 1, p.99-129.

Vanuxem, L.
1840: Fourth Annual Report to the Geological Survey of the Third District; New York Geological Survey Annual Report 4, p.355-383.

Vine, J., and Tourtelot, E.
1970: Geochemistry of black shale deposits - a summary report; Economic Geology, Vol. 65, p.253-272.

Wedepohl, K.H. (ed.)
1969: "Handbook of Geochemistry", Springer-Verlay, New York.

Williams, D.A., and Rae, A.M.
1983: Paleozoic geology of the Ottawa-St. Lawrence Lowland, southern Ontario, p.107-110, in Summary of Field Work, 1983, by the Ontario Geological Survey, edited by John Wood, Owen L. White, R.B. Barlow, and A.C. Colvine, Ontario Geclogical Survey, Miscellaneous Paper 116, 235p.

Williams, D.A., and Wolf, R.R.
1982: Paleozoic geology of the northern part of Ottawa-St. Lawrence Lowland, southern Ontario, p.132-134; in Summary of Field Work, 1982, by the Ontario Geological Survey, edited by John Wood, Owen L. White, R.R. Barlow, and A.C. Colvine, Ontario Geological Survey, Miscellaneous Paper 106, 235p.

Williams, D.A., Rae, A.M., and Wolf, R.R.
1984: Paleozoic geology of the Ottawa area, southern Ontario; Ontario Geological Survey, Preliminary Map P.2716, Geology 1982.

Winder, C.G., and Sanford, B.V.
1972: Stratigraphy and paleontology of the Paleozoic rocks of southern Ontario; Excursion A45-C45 (Guidebook) 24th Session, International Geology Conference, Montreal, Quebec.

Winder, C.G., Barnes, C.R., Telford, P.G., and Uyeno, T.T.
1975: Ordovician and Devonian stratigraphy and conodont biostratigraphy of southern Ontario; in Field Excursions Guidebook, Part B: Phanerozoic Geology, P.G. Telford (editor), Geological Association of Canada, Waterloo, Canada, p.119-160.

Wolf, R.R.
1985: Paleozoic Geology of Cockburn Island, District of Manitoulin; in Summary of Field Work and other Activities 1985, by the Ontario Geological Survey, p.155-158, edited by J. Wood, O.L. White, R.B. Barlow, and A.C. Colvine, Ontario Geological Survey, Miscellaneous Paper 126, 351p.

APPENDIX I - Organic Geochemical Techniques

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A. 1.1 INTRODUCTION

Geochemical analyses of oil shales have been undertaken to evaluate their potential as a source of petroleum products and to assist in the geological studies into the factors controlling their potential. Oil shales are not clearly defined (Tissot and Welte 1978; Macauley et al. 1985). They are sedimentary rocks which contain organic matter sufficient to produce petroleum products in economic amounts when heated without the presence of oxygen. This heating or retorting without oxygen is a form of pyrolysis. Organic-rich sedimentary rocks may be combusted in oxygen or air to yield heat and may have value for other processing, but these aspects are beyond the scope of this geochemical study. The current evaluation has stressed their potential as a source of crude petroleum products.

The petroleum product yield, both specific products and amounts, depends upon the commercial process used. It also depends upon the organic matter content and type of organic matter present and in the rock-factors controlling its "richness". This richness and geological/geochemical control of richness is being evaluated by geochemical analyses of rock samples. These analyses can be grouped
into three categories:

1. Pyrolysis yield

The standard assay for yield upon retorting pyrolysis is the Fischer Assay. This analysis requires large (200 g) samples and is relatively expensive. However, a large Fischer Assay data base exists for many oil shales. Retorting with a hydrogen atmosphere can enhance yields and this possibly was evaluated by Hytort (R) retorting.

2. Organic matter content

The organic matter content of specific samples has been assessed by measurement of their total organic carbon (TOC) content. Carbon makes up from 60 to 90 weight percent of sedimentary organic matter. For formations of limited depth and areal extent containing a similar type of organic matter - the case for Ontario's potential oil shales - the weight percent carbon is much more limited and TOC accurately assesses the organic matter content.

3. Organic matter geochemistry

The pyrolysis yield of oil shales also depends upon the chemistry of the organic matter. Hydrogen-rich organic matter yields more petroleum-like pyrolysis products, termed pyrolysates, than hydrogen-poor organic matter. Pyrolysis yields seem to be limited more by organic hydrogen than by organic carbon content. Thus, the nature of the organic matter must be assessed in the evaluation of this resource. These studies also assist in the determination of geological controls of oil shale richness.

Organic matter in sedimentary rocks is operationally divided into solvent-soluble bitumen and solvent-insoluble kerogen. The former more closely approaches the composition of crude oils, being relatively enriched in hydrogen, and it is generally considered to be derived from the thermal maturation of kerogen. The amount of bitumen generated increases as the hydrogen-richness of the initially-deposited organic matter increases and its relative proportion to kerogen increases with maturation level. By definition, all oil shales contain indigenous organic matter (kerogen) at low to intermediate thermal maturation levels.

The organic matter geochemistry is assessed by a number of techniques. Temperature-programmed pyrolysis, including Rock-Eval analysis, permits estimates of the bitumen/kerogen proportion and gas chromatography/mass spectrometry of the pyrolysates helps characterize the chemistry of these factors. The origin and thermal maturation level of kerogen is assessed by elemental analysis, infrared spectroscopy and stable carbon isotopic (13C/12C) analyses.

The depositional environment of these organic-rich rocks is partially assessed by geochemical analyses. Parameters determined include carbonate content (as total inorganic carbon or TIC), total sulphur content, phosphorous content (as P2O5), and stable carbonate isotope analyses of the carbonate minerals.

This comprehensive suite of geochemical analyses provides the geochemical basis for the evaluation of this oil shale resource. Adequate evaluation, however, requires the integration of this data with geological, engineering and economic studies.

A. 1.2 TOTAL ORGANIC CARBON (TOC)

The following description is taken from Churcher (1984) and Churcher and Dickhout (1987). About 0.2 to 0.5 gram, finely crushed (<200 mesh) rock samples are weighed onto glass microfibre filter papers. The filter papers are placed on Hirsch funnels and the samples acidified with warm 30% HCl and then thoroughly washed with deionized water. Bituminous samples are wetted with a drop of methanol prior to acidification. The inorganic-carbon-free sample contained inside the filter paper is dried and then combusted at about 800½C in a Lindburg tube furnace. The combustion products are swept with CO2-free oxygen through a water sorban 1 (Drierite) and then into a Beckman non-dispersive infrared detector where the CO2 from combustion of organic matter is detected. Quantification is accomplished by comparing the area of the CO2 peak from sample combustion to that of gravimetrically prepared charcoal-pumice standards. This calibration of the detector response is made daily. In addition, two homogeneous "in house" standards are prepared from the Kettle Point Formation material are analyzed frequently to confirm reproducibility. These standards and other standards were analyzed by other laboratories and the agreement with our results is very good (see Table 13 from Churcher 1984). Churcher (1984) evaluated the major sources of bias in this analysis, especially the potential loss of organic matter during acidification and methanol addition as well as the potential addition of carbon via the methanol. No significant bias was documented. For the major "in house" standards analyzed from 8 to 39 times the relative standard deviation was always less than 5.5% and the mean differed from the average value reported by all other labs by less than 5.4% except for CLGD-Composite where a difference of about 12% was found (see Table 13). We therefore feel the TOC analyses are generally accurate and reproducible to within about 5% over the TOC concentration range of 4% to 15%. Poorer accuracy and precision may occur at lower concentrations, but accuracy at these lower concentrations is of less significance in evaluating these potential oil shales.

Laboratory Analysis	CLGD - Composite	CLGD-acid washed	Cr	Cr-acid washed	SY-1	KP-IHS Low	KP-IHS High	METHOD	COMMENTS
Paul Gunther Petro Can.	3.4	-	-	-	-	0.3	-	Leco WR-12	TOC after acidification
U of W Newton Milne, Chemical Eng.	2.4 to 3.6	8.4	6.2-7.0	15.7	-	0.4	12.7	Elemental Analysis	Total Carbon*
U of W R. Dickhout Earth Sciences	-	-	-	-	-	9.8	-	Ascarite (CO_2 Absorption)	TOC after acidification
Hagar	4.2	-	-	-	-	- -		Leco WR-12	TOC after acidification
M.H.W, Labs Houston, Texas	-	-	-	-	-	9.9	-	Elemental Analysis	Total Carbon*
Average	3.8	8.4	6.6	15.7	usable value =0.02	9.6	12.7	--	--
Organic Geochemistry Lab (U.W.)								As outlined in this paper	
Mean	3.97	8.5	6.7	14.7	0.05	0.6	12.5		
Standard Deviation	0.22	0.51	0.23	0.92	0.05	0.22	0.28		
Range	3.6-4.4	8.0-8.9	6.3-7.0	14.1-15.5	0.014-0.097	9.1-9.9	12.0-12.9		
No. of Samples	47	3	19	2	3	39	8		

TIC Values: CLDG = 7.1 0.6
Cr = 7.0 0.4
S-low = 0.167
KPIHS-high =0.14

*Values of TOC obtained by the subtraction of total inorganic carbon (TIC) obtained by method outlined in Barker and Chatten (1982).

TABLE 13 - Comparison of TOC results from organic geochemistry (UW) and other Laboratories (from Churcher 1984).

A. 1.3 FISCHER ASSAY (FA)

The standard method for evaluating the oil yield upon retorting oil shales is the Fischer Assay. The technique is described by Hubbard (1965). All analyses were performed by the Analytical Services Laboratory (L.C. Cox, Manager), Colorado School of Mines Research Institute, P.O. Box 112, Golden, Colorado. One hundred grams of less than 8 mesh shale chips are added to the retort in five layers to promote effective pyrolysis. The retort is heated without air entry to 500°C over 40 minures and held at 500°C for 20 minutes. The pyrolysate is collected in an attached receiver held between 0°C and 37.8°C. The volume and weight of condensate (oil plus water) is determined and, if sufficient oil is present, its specific gravity is determined. The volumes of oil and water produced are converted to units of US gallons per ton or litres per metric ton. Unaccounted sample weight loss (or gain) is also reported and the difference, if a loss, is usually attributed to the generation of uncondensed gases. Hubbard (1965) reports that oil yields for an oil shale with a mean oil yield of 39.5 gallons per ton had a range from 38.3 to 40.2 or within 3% for twelve replicate analyses. Water and oil specific gravity showed a similar small range of values.

A. 1.4 BITUMEN AND KEROGEN ISOLATION

Solvent Extraction for Bitumen Isolation

After experimenting unsuccessfully with a rapid chloroform extraction of bitumen, a regular soxhlet extraction procedure was employed. This involves the continuous extraction of rock by chloroform over a 12 to 14 hour period. The chloroform reservoir is heated, the chloroform vapours condensed and recirculated through the rock powder (greater than 200 mesh). The chloroform is then concentrated to about 1 cm^3 by evaporation in a modified Kuderna-Danish concentrator. This procedure extracts the chloroform-soluble organics (bitumen) and retains those less volatile than chloroform which has a boiling point of about 62°C.

Kerogen Isolation

Initially, powdered (less than 100 mesh) rock samples were alternately digested in 50% HCl and 50% HF to remove inorganic mineral matter. The kerogen was further purified from inorganically contaminated kerogen by density difference in a ZnCl2 solution in which the purest kerogen rose to near the top of the solution. This procedure was found to leave up to 37% inorganic material in the kerogen. Subsequent kerogen isolations involved initial soxhlet extraction with chloroform to remove bitumen, followed by leaching with concentrated HCl and HF to remove inorganic minerals. The acid-leaching was repeated once. The kerogen concentrate was repeatedly rinsed with deionized water, separated by centrifugation with the final wet isolate allowed to dry at room temperature before storage over a desiccant (Drierite). Generally, the kerogen was found to contain less than 20% inorganic impurities.

This kerogen was then subjected to various geochemical analyses including ash content, elemental carbon and hydrogen analysis, pyrolysis and infrared absorption studies.

A. 1.5 ASH CONTENT OF KEROGEN

The kerogen extract is heated to about 80°C and cooled in a water vapour free container. An aliquiot of about 0.1 gram is then weighed, combusted at 600°C for 1 hour, cooled and reweighed. The residual material is taken as inorganic ash.

A. 1.6 WHOLE ROCK ANALYSIS

Approximately 10 mg of pulverized whole rock powder is placed in the quartz tube of an Envirochem model 787 high temperature furnace. The sample is purged with helium for a few minutes, then heated from ambient temperature to 300°C at 40° min and held at the final temperature until the signal from an FID detector monitoring the evolution of hydrocarbons has returned to the baseline. At this point the hot zone is removed from the sample, the pyrolysis products having been collected on a tenax trap.

With the completion of the cycle, the tenax is thermally desorbed, and a small fraction of the products split to a flame ionization detector to produce a "bitumen, total hydrocarbon" peak. The rest is transferred onto a narrower bore trap for subsequent desorption onto a 60 m DB5 quartz capillary column for chromatography. Here the individual hydrocarbon components are resolved before detection by an FID detector. Pyrolysis components are identified on the basis of retention time determined with pure standards.

The hot zone of the high temperature furnace is then repositioned over the sample and heating is resumed at the previous rate up to 700^{o}C. This results in the thermal breakdown of kerogen, the products of which are handled in the same way as those of bitumen. The initial split to an FID detector generates a "kerogen, total hydrocarbon" peak and the kerogen pyrolysate chromatography carried out as with the bitumen pyrolysate.

The chromotograph uses, in both cases, a 60 m DB5 column, heated from 35 to 280^{o}C at a rate of 8^{o}C/min and held at 280^{o}C for 10 min.

The following parameters are determined from the chromatograms.

1. Transformation Ratio

The transformation ratio is defined as bitumen/bitumen+kerogen and is obtained from the total hydrocarbon responses (bitumen, total hydrocarbon/(bitumen, total hydrocarbon plus kerogen, total hydrocarbon)). It is an indicator of thermal maturation, i.e. maturity is greater with increasing value.

2. Pristane/phytane Ratio

The peak areas of these two isoprenoid compounds are obtained from the bitumen pyrochromatogram. The pristane/phytane ratio is commonly used to indicate the lacustrine/terrestrial nature of the original organic material. Generally, ratios lower than 1.5 indicate a marine shale-carbonate sequence while ratios greater than 3.0 indicate a significant amount of terrestrial source material. This ratio can be affected by depositional environment (i.e. whether the environment was oxidizing or reducing and by maturation).

3. Odd-even Preference (OEP)

The predominance of odd or even n-alkanes is determined by summing the peak areas on odd and even n-alkanes in the bitumen pyrochromatogram. The C16 to C20 n-alkanes are examined and the ratio established according to the method of Scalan and Smith (1970).

4. p^{+}m-xylene/n-octene Ratio

This ratio is calculated from the areas of the appropriate compound peaks on the kerogen pyrochromatogram. It defines the aromaticity of the kerogen and serves as an indicator of source material type according to the classification scheme of Larter and Douglas (1978). The scheme is defined as follows:

Kerogen Type	Ratio Value
type I: alignites;	$R < 0.4$
type II: sporinites;	$0.4 < R < 1.3$
type III: vitrinites;	$R > 1.3$

For quality control purposes, four samples of Collingwood Formation from borehole CLGD-4 at a depth of 70.31 to 70.41 m were pyrolyzed and the bitumen pyrolysate (room temperature to 300°C) analyzed by gas chromatography. The values of various geochemical parameters calculated from the chromatgram are shown in Table 14. Interpretation of the results must consider the 9 to 24% standard deviations observed for these replicate analyses.

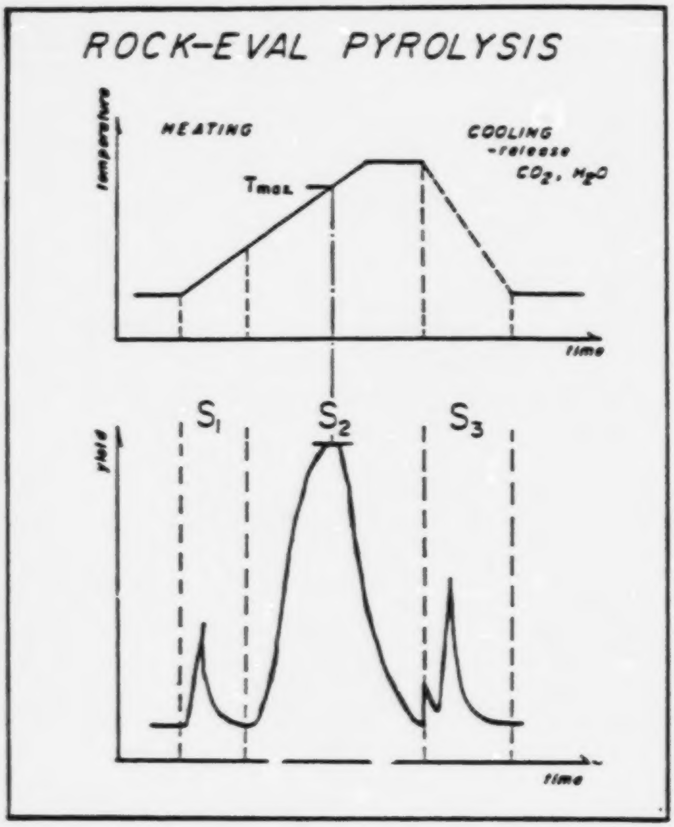
Table 14. Analyses from a Collingwood sample-Bitumen Pyrolysate.

	Parameter				
Replicates	CPI	OEP	PR/PH	PR/C17	PB/C18
1	1.06	1.03	1.44	1.36	0.991
2	0.882	0.847	1.48	1.30	0.811
3	0.954	0.943	1.27	1.08	0.900
4	0.868	0.864	0.831	0.978	0.935
Mean	0.941	0.906	1.26	1.18	0.912
Standard Deviation, S	0.088	0.101	0.297	0.180	0.075
S as % of Mean	9.35%	11.0%	23.6%	15.3%	8.22%

A. 1.7 ROCK-EVAL ANALYSIS

Rock-Eval whole-rock pyrolysis was conducted by the Institute of Sedimentary and Petroleum Geology (I.S.P.G.), Calgary. The technique, developed by Espatalie, et al. (1977), is described in Tissot and Welte (1978). It involves heating a finely crushed rock powder progressively to 500½C and measuring evolved hydrocarbons. Hydrocarbons evolve in two stages; those already present in the rock in a free state, or bitumen components, evolve at 200 to 250°C and are defined as S1 yield. The pyrolysis of kerogen occurs at higher temperatures (400 to 500°C) and generates second stage hydrocarbons terms S2 yield. Oxygen-containing volatiles, namely CO2 and water, derived from oxygen-containing kerogen structures evolve at high temperatures and are known as S3 yield. Figure 14 depicts a recorded pyrolysis sequence and additional information that can be obtained from the pyrolysis.

In viewing information obtained from the pyrolysis, it is useful to consider that bitumen is a product of thermally matured kerogen. Therefore, the amount of bitumen (S1) can be considered the "bitumen show" of the rock. The ratio of bitumen to bitumen plus kerogen represents the amount of thermal maturation endured, and a transformation ratio [(S1/(S1 + S2)] can therefore be used as a maturation indicator. Tmax, the temperature of maximum hydrocarbon generation, is also indicative of thermal maturation.


ROCK-EVAL PYROLYSIS
temperature
HEATING
COOLING
-release
CO2, H2O
Tmax
time
S1
S2
S3
yield
time

Information obtained for this study:

S1- oil or gas show (kg./ton rock)
S1/S1+S2- transformation ratio
Tmax.- temperature of maximun hydrocarbon generation (°C)
S1+S2- petroleum potential (kg./ton rock)
S2/TOC- hydrogen index (mg. yield/g. TOC)
S3/TOC- oxygen index (mg. yield/g. TOC)

Fig. 14. Rock-Eval pyrolysis cycle and typical detector response (from Sacheli 1985).

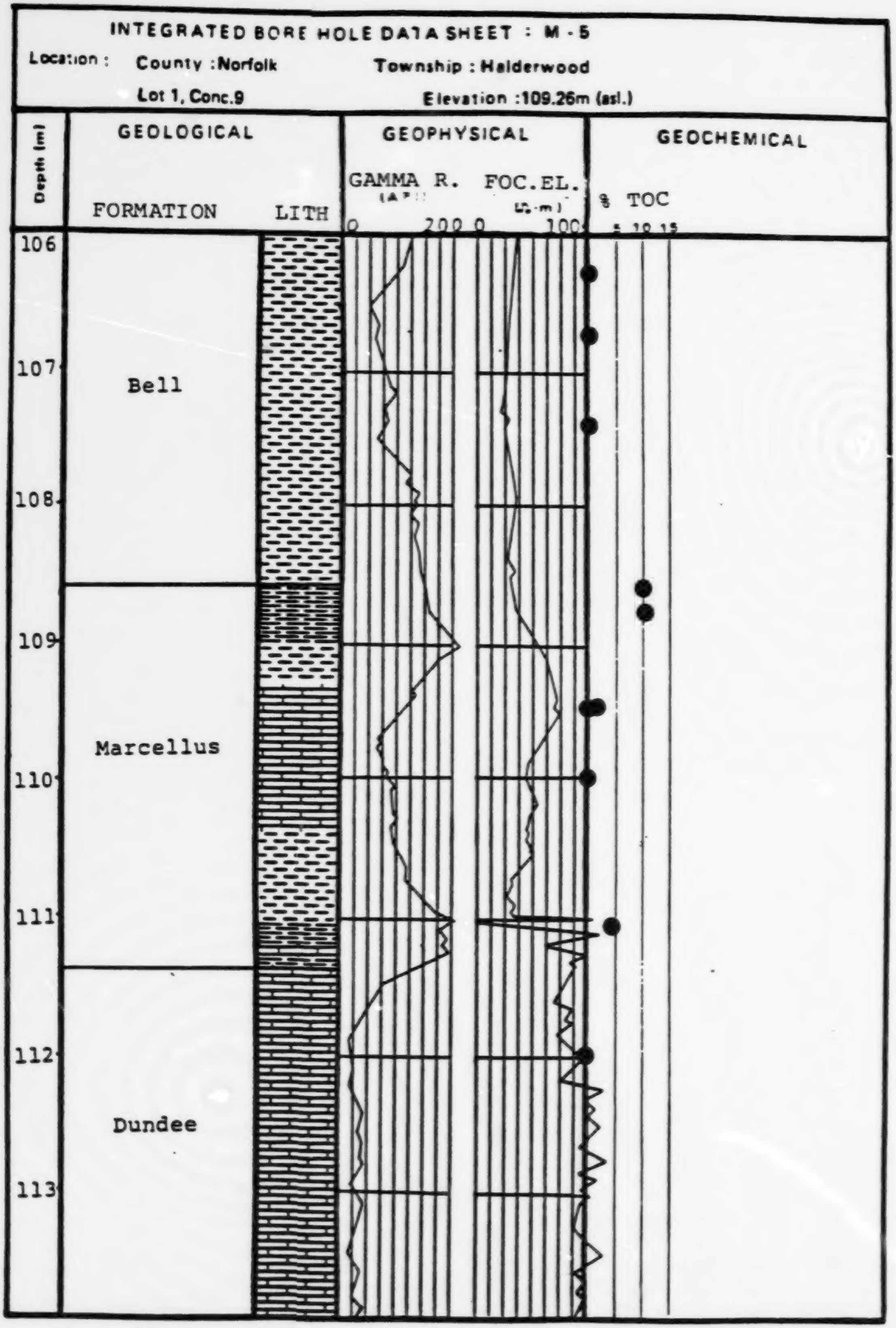
Tissot and Welte (1978) indicate that the Tmax. increases progressively with maturation, but numerical scaling is dependent on the rate of pyrolysis heating. Tmax can be correlated with other maturation indicators such as vitrinite reflectance (Tissot and Welte 1978). The petroleum potential ($S_1 + S_2$) reflects the overall organic richness of the shale. Samples with high petroleum potential are rich in bitumen and/or kerogen or both.

Kerogen typing can also be performed by Rock-Eval pyrolysis using hydrogen and oxygen indices, which are calculated by S_2/TOC and S_3/TOC respectively. A modified Van Krevelen diagram can be constructed to determine organic matter type. Espatalie, et al. (1977) discusses the correlation between Rock-Eval calculated indices and elemental concentration in kerogens. Major limitations of Rock-Eval kerogen typing are discussed by Snowdon (1984).

APPENDIX 2

INTEGRATED DRILLHOLE LOGS

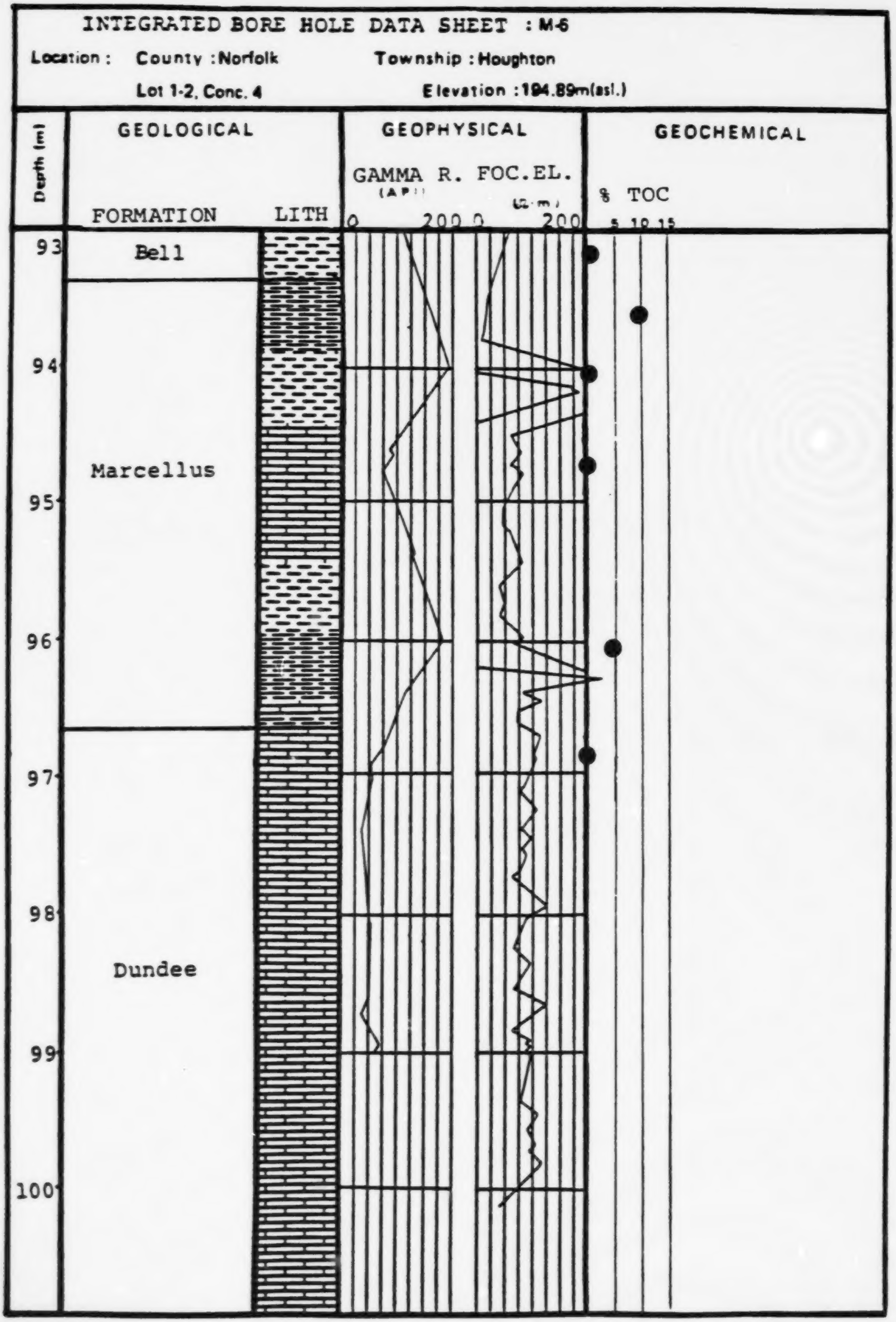
The following logs graphically display information for each of the OGS boreholes drilled into or immediately adjacent to the Marcellus Formation. Of the 6 holes included (M-5 to M-9, and OGS-82-3), 4 intersected Marcellus (M-5, M-6, M-8 and OGS-82-3). Detailed description of each at the 6 holes has already been released (see Johnson 1985, Johnson *et al*. 1985). The lithology log presented here is quite general and intended to indicate gross lithological units. Geophysical logs were made in some of the holes but not all, depending on whether or not Marcellus was intersected (i.e. no logs for M-7 and M-9) or for reasons connected with the drilling (i.e. the logs start too low to pick up the Marcellus in OGS-82-3).



INTEGRATED BORE HOLE DATA SHEET : M-5

Location : County :Norfolk Township : Halderwood

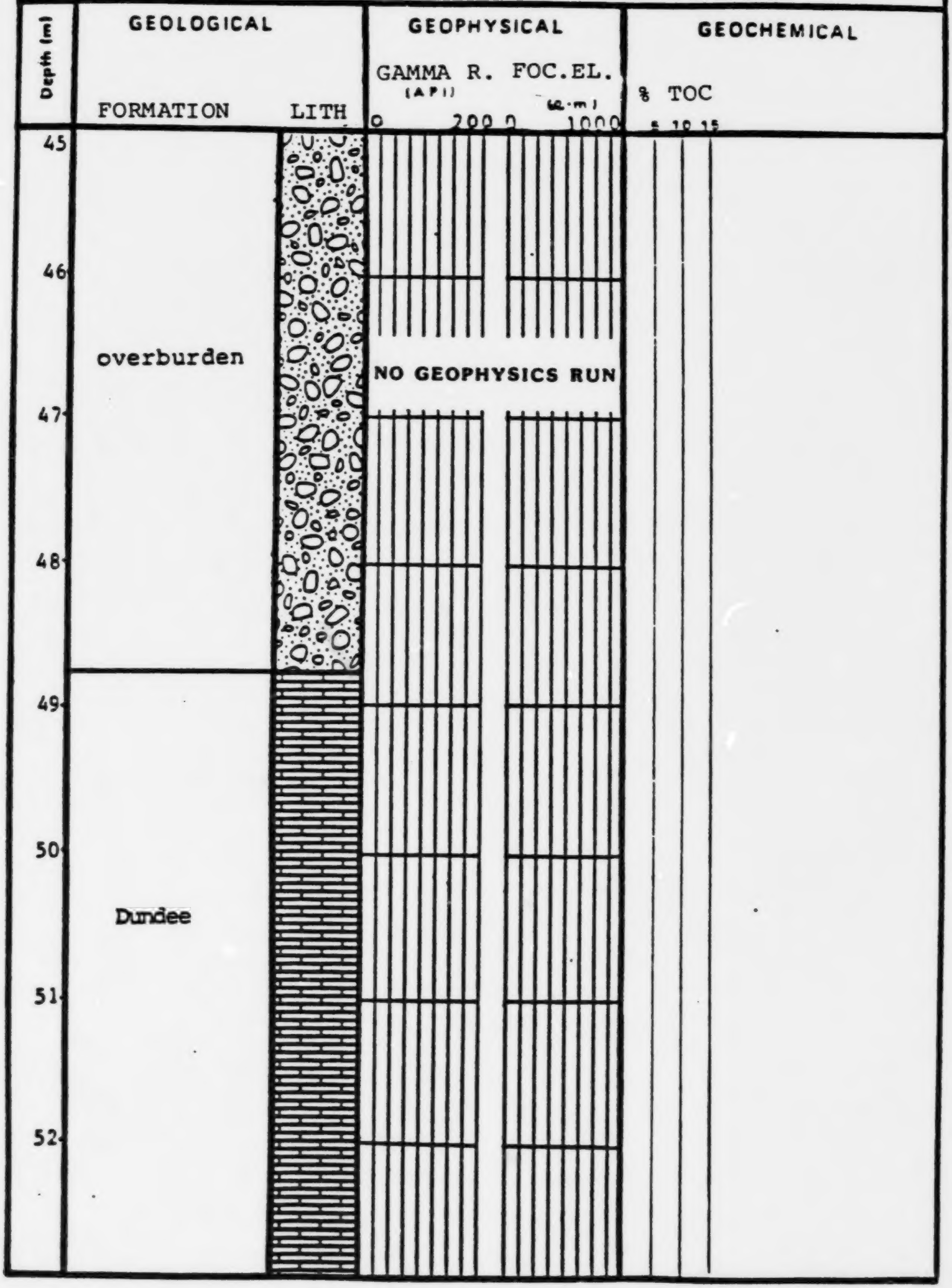
Lot 1, Conc.9 Elevation :109.26m (asl.)


INTEGRATED BORE HOLE DATA SHEET : M-6
Location : County : Norfolk
Township : Houghton
Lot 1-2, Conc. 4
Elevation : 194.89m(asl.)
Depth (m)
GEOLOGICAL
FORMATION
LITH
GEOPHYSICAL
GAMMA R.
(API)
FOC.EL.
(Ω·m)
0
200
0
200
GEOCHEMICAL
% TOC
5
10
15
93
94
95
96
97
98
99
100
Bell
Marcellus
Dundee

INTEGRATED BORE HOLE DATA SHEET : M - 7

Location : County : Elgin Township : Bayham

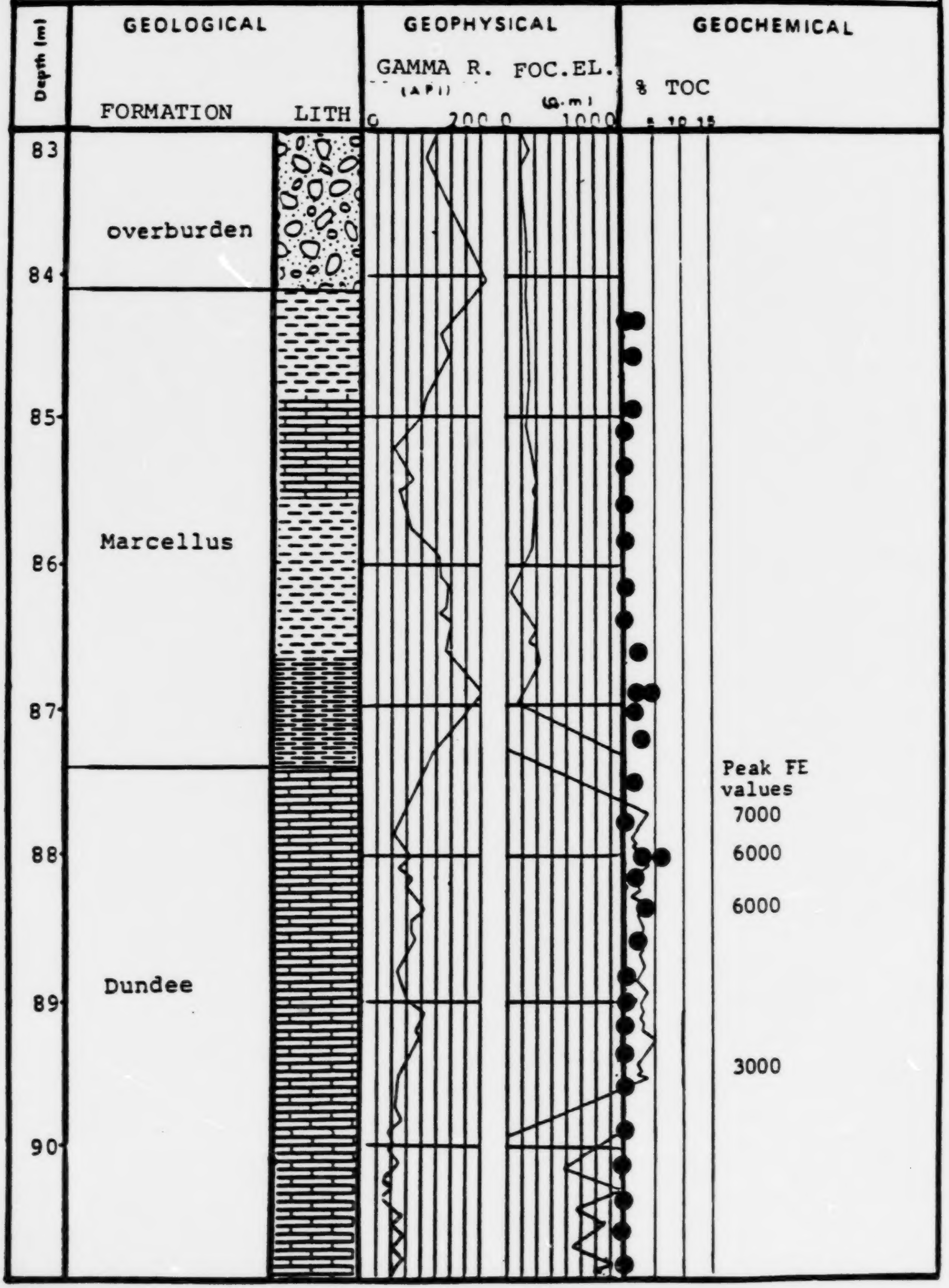
Lot 6, Conc. III Elevation : 180.75m (asl.)

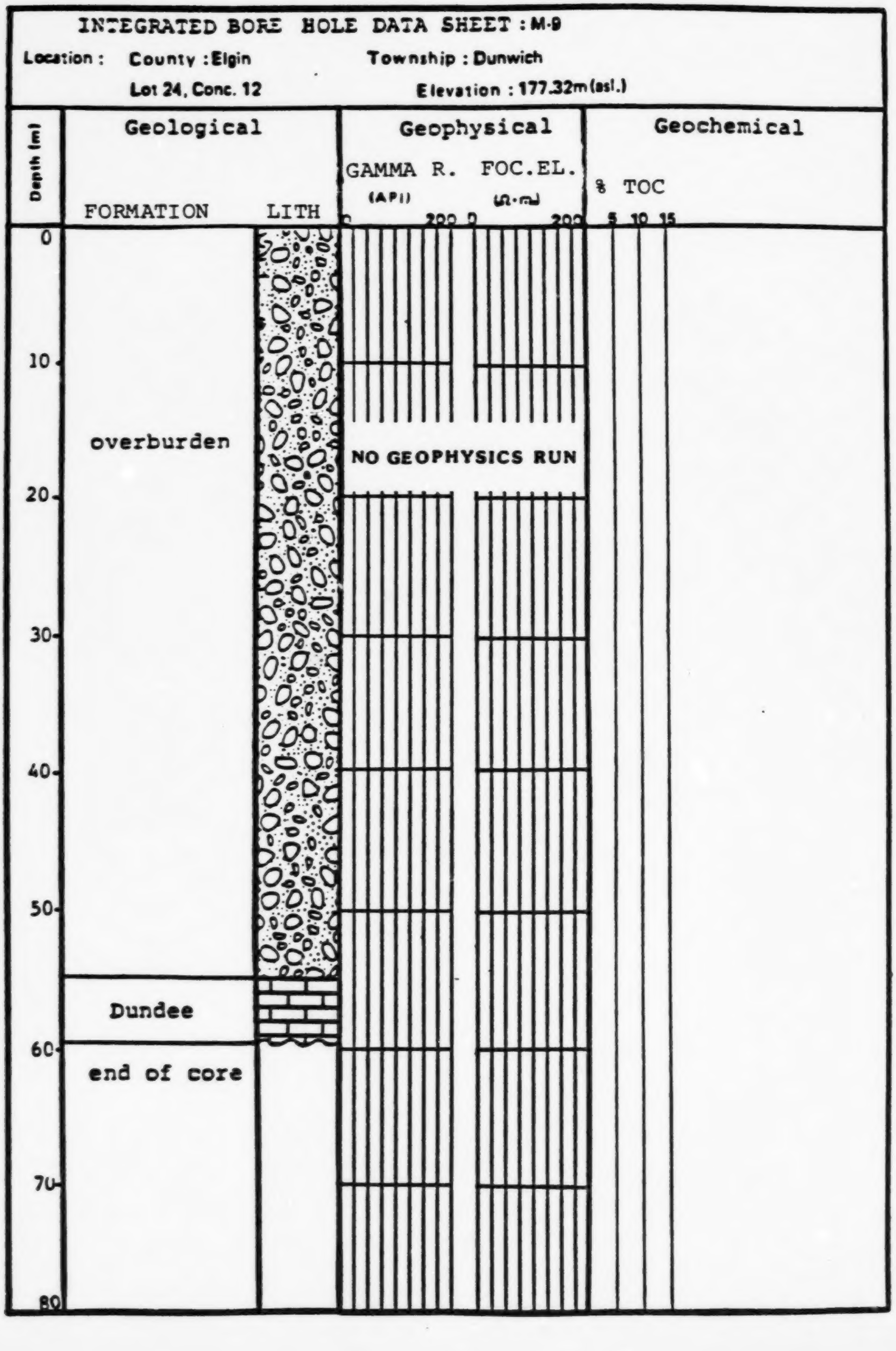

Depth (m)
GEOLOGICAL
FORMATION
LITH
GEOPHYSICAL
GAMMA R.
(API)
0
200
FOC.EL.
(Ω·m)
0
1000
GEOCHEMICAL
% TOC
5 10 15
45
46
47
48
49
50
51
52
overburden
Dundee
NO GEOPHYSICS RUN

INTEGRATED BORE HOLE DATA SHEET : M-8

Location : County : Elgin Township : Malahide

Lot 26, Conc. 1 Elevation : 204.48m (asl.)

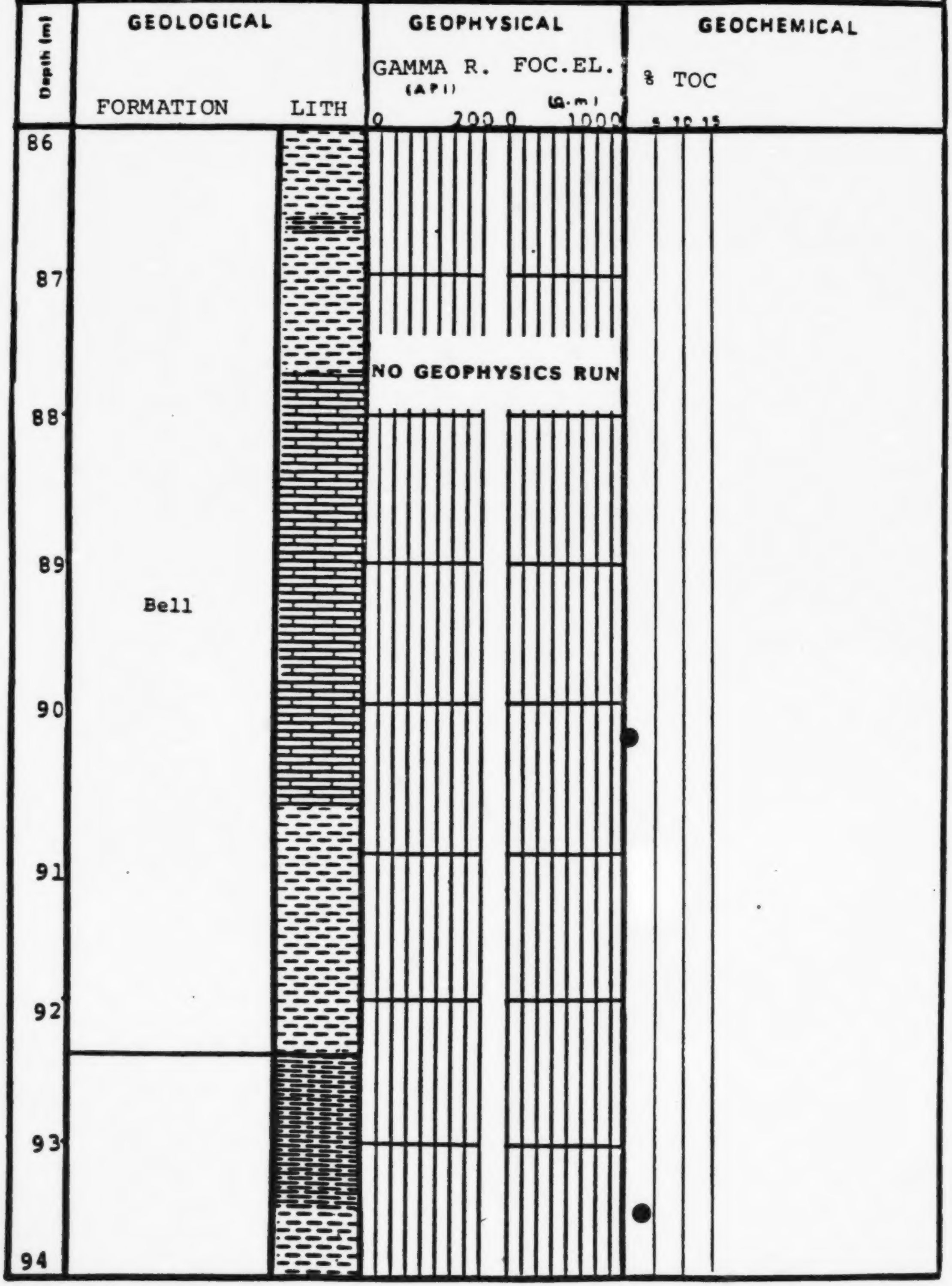



INTEGRATED BORE HOLE DATA SHEET : M-9
Location : County : Elgin
Township : Dunwich
Lot 24, Conc. 12
Elevation : 177.32m (asl.)
Depth (m)
Geological
FORMATION
LITH
Geophysical
GAMMA R.
(API)
0
200
FOC.EL.
(Ω·m)
0
200
Geochemical
% TOC
5
10
15
0
10
20
30
40
50
60
70
80
overburden
Dundee
end of core
NO GEOPHYSICS RUN

INTEGRATED BORE HOLE DATA SHEET : OGS - 82 - 3 Port Stanley 1 of 2

Location : County : Elgin Township : Yarmouth

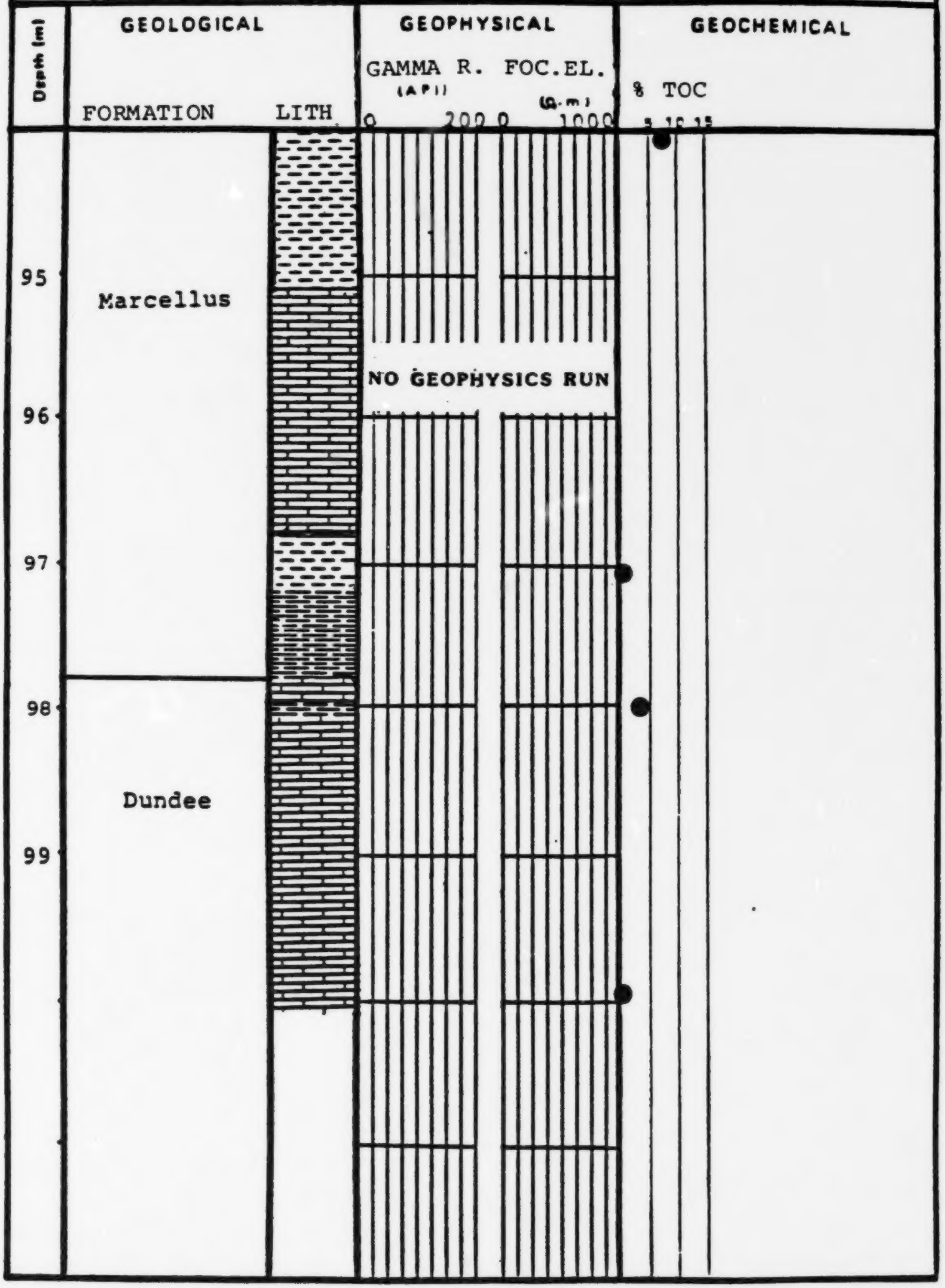
Lot 9, Con. 1 Tract 3 Elevation : 211.4m (asl.)



INTEGRATED BORE HOLE DATA SHEET : OGS - 82 - 3 Port Stanley 2 of 2

Location : County : Elgin Township : Yarmouth

Lot 9, Con. 1 Tract 3 Elevation : 211.4m (asl.)


Depth (m)
GEOLOGICAL
FORMATION
LITH
GEOPHYSICAL
GAMMA R.
(API)
0
200
FOC.EL.
(Ω.m)
0
1000
GEOCHEMICAL
% TOC
5
10
15
95
96
97
98
99
Marcellus
Dundee
NO GEOPHYSICS RUN

APPENDIX 3

CATALOGUE OF OIL AND GAS EXPLORATION WELLS, LAKE ERIE

The following, mostly gas exploration wells, were used to produce the isopach map (Back Pocket) for the Marcellus Formation. This list does not include all wells drilled in the Lake Erie area. Many wells had geophysical logs/samples which did not prove or disprove the presence of Marcellus Formation, therefore, only those wells were used which had logs/samples which positively indicated the presence (or absence) of the formation. For additional information on these and other exploration wells in the area contact Petroleum Resources Section, Ministry of Natural Resources, 58 Central Avenue, London, Ontario. Included are gamma-ray and focussed electric logs. Other types of logs (e.g. density, neutron caliper, sonic) were also taken in these holes and are released in separate open file reports (Johnson 1985 and Johnson *et al*. 1985).

Map No.	Well Name	Lots and Conc or Block and tracks
1	M-9	Lot 24, Conc. XII
2	OGS-82-3	Lot 9, Conc. I
3	M-8	Lot 26, Conc. I
4	M-7	Lot 6, Conc. III
5	M-6	Lots 1 and 2, Conc. IV
6	M-5	Lot 1, Conc. IX
7	Shawee UBR Malahide 2.31.III	Lot 31, Conc. III
8	Forbes #9 Malahide 2.91.NTR	Lot 91, Conc. NTR
9	C-G-33119/Malahide 4.21.I	Lot 21, Conc. I
10	Bluewater S. Dorchester 7-16-11	Lot 16, Conc.VIII
11	Anschutz (Can.) Exp. Ltd.	110-S
12	CG 13030	113-C
13	CG 13124	104-N
14	C-Amoco 13104	103-P
15	C-Pan Am 13038	102-B
16	CG 13491	101-I
17	C-Amoco 13093	100-A
18	CG 13216	99-I
19	CG 13472	97-E
20	CG 13168	126-F
21	CG 13414	95-M
22	CG 13746	95-U
23	CG 13553	125-C
24	CG 13658	124-C
25	CG 13294	123-D
26	CG 13224	121-A
27	CG 13325	120-I
28	CG-Pan Am 13053	119-A
29	CG 13525	118-B
30	CG 13524	118-C
31	CG 13398	117-K
32	Anschutz	116-Y
33	Anschutz #3	115-G
34	Anschutz (Can.) Exp. Ltd.	161-M
35	CG Pan Am Petrol. Ltd.	161-W
36	CG Pan Am Petrol. Ltd.	113-U
37	Anschutz #1	162-G
38	CG 13519	159-D
39	CG 13715	160-H
40	CG 13340	158-B
41	CG 13578	157-F
42	CG 13579	157-G
43	CG 13122	157-C
44	CG 13006	157-A
45	CG 13212	155-E
46	CG 13296	154-E
47	CG 13426	154-C
48	CG 13836	126-O
49	CG 13168	126-M

CG = Consumers Gas Ltd.

Map No.	Well Name	Lots and Conc or Block and tracks
50	CG 13556	126-N
51	CG 13100	126-P
52	CG 13313	152-A
53	CG 13736	151-D
54	CG 13332	152-C
55	CG 13776	188-E
56	CG-Pan Am 13041	187-D
57	CG 13519	157-D
58	CG 13164	157-M
59	CG 13582	157-N
60	CG 13584	157-S
61	CG 13777	157-V
62	CG 13042	157-R
63	CG 13803	157-Y
64	CG 13010	185-D
65	CG 13522	185-A
66	CG 13498	185-I
67	CG 13586	185-E
68	CG 13046	184-J
69	CG 13750	185-M
70	CG 13589	185-J
71	CG 13807	185-T
72	CG 13715	160-I
73	CG 13628	182-A
74	CG 13598	183-G
75	CG 13700	183-K
76	CG 13336	183-T
77	CG 13601	183-V
78	CG 13396	183-S
79	CG 13600	183-R
80	CG 13394	183-X
81	CG 13465	183-N
82	CG 13599	182-K
83	CG 13337	182-K
84	CG 13457	182-S
85	CG 13397	183-P
86	CG 13393	182-Y
87	CG Pan Am 13032	161-W
88	CG 13733	181-C
89	CG 13633	180-I
90	Anschutz #2	179-J
91	CG 13116	162-Y
92	Anschutz #3	179-G
93	Anschutz Can. Expl. Ltd.	178-L
94	CG 13515	220-H
95	CG 13718	221-R
96	CG 13516	220-N
97	CG 13507	220-P

CG = Consumers Gas Ltd.

Map No.	Well Name	Lots and Conc or Block and tracks
98	CG 13610	221-J
99	CG 13192	221-H
100	CG 13193	221-D
101	CG 13244	221-P
102	CG 13253	221-O
103	CG 13611	221-N
104	CG 13262	220-P
105	CG 13609	220-C
106	CG 13625	220-M
107	CG 13510	175-V
108	CG 13385	238-R
109	CG 13502	284-C
110	CG 13560	313-J
111	C.W.P. Taylor Dover 69-10	46-E
112	Pembina #4	63-K
113	Pembina #1 (5872)	63-A
114	CG 13465	183-N
115	Anschutz #4 (5444)	129-R
116	CG-Pan Am 13002	185-O

CG = Consumers Gas Ltd.

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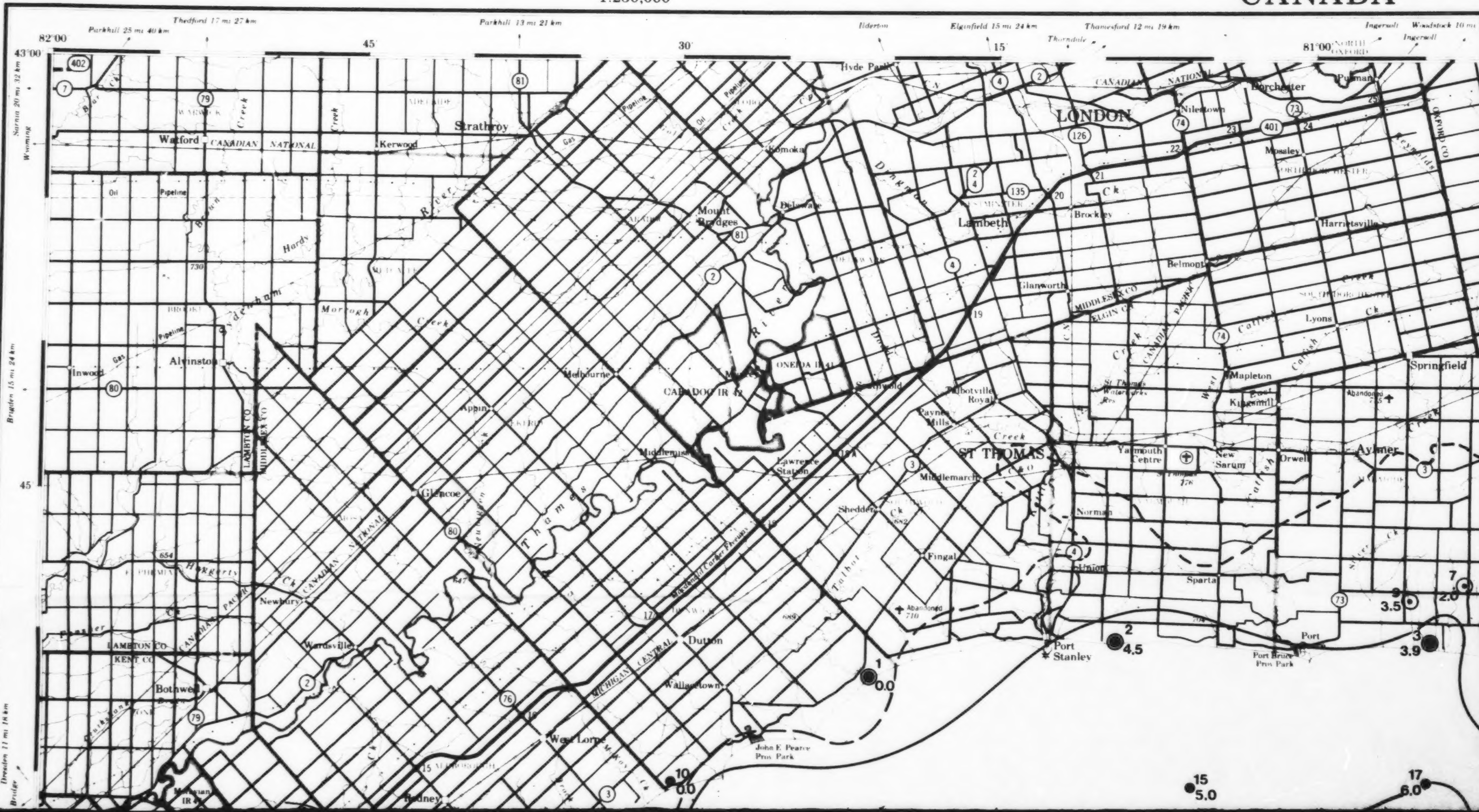
CANADA

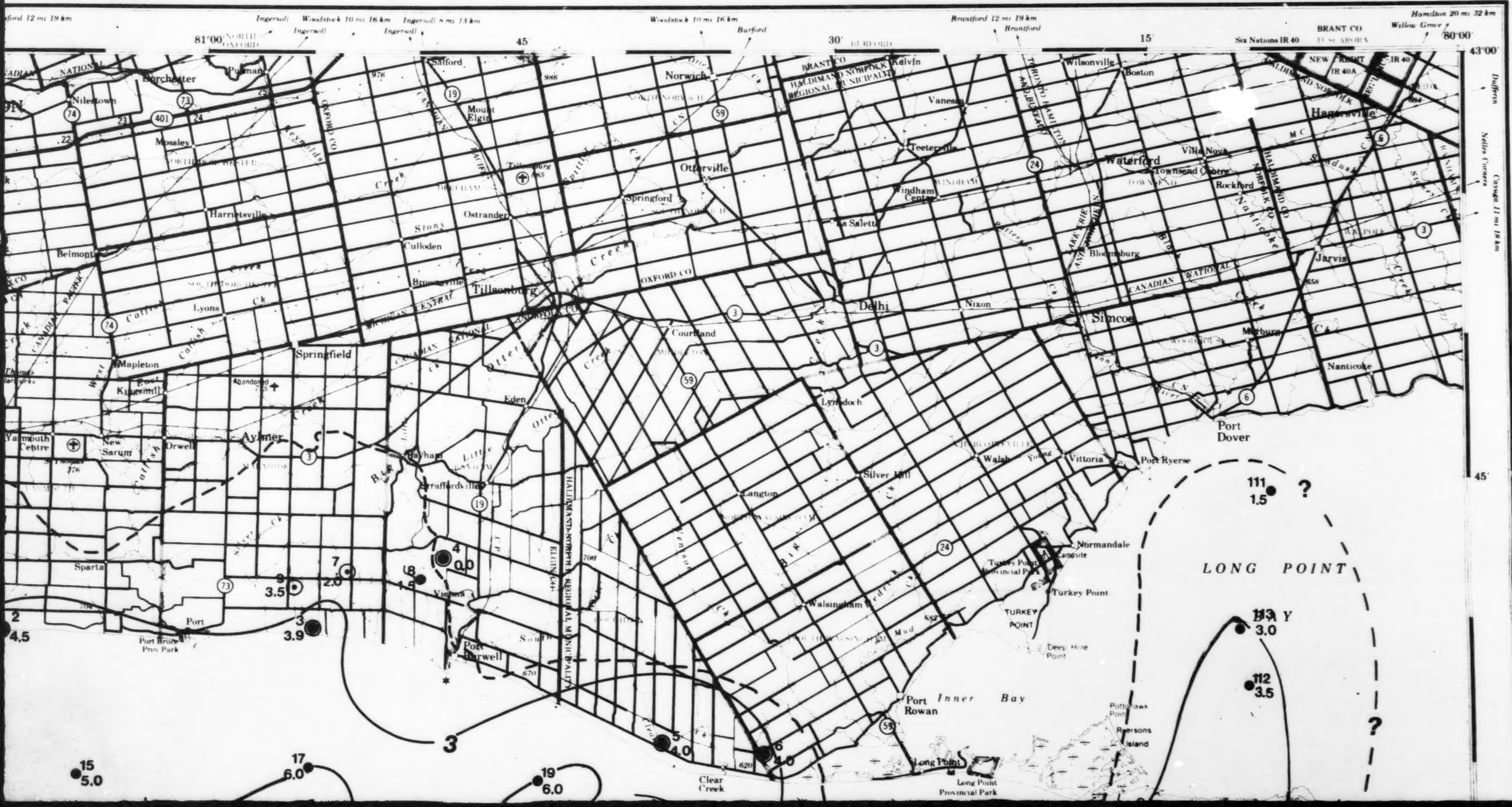


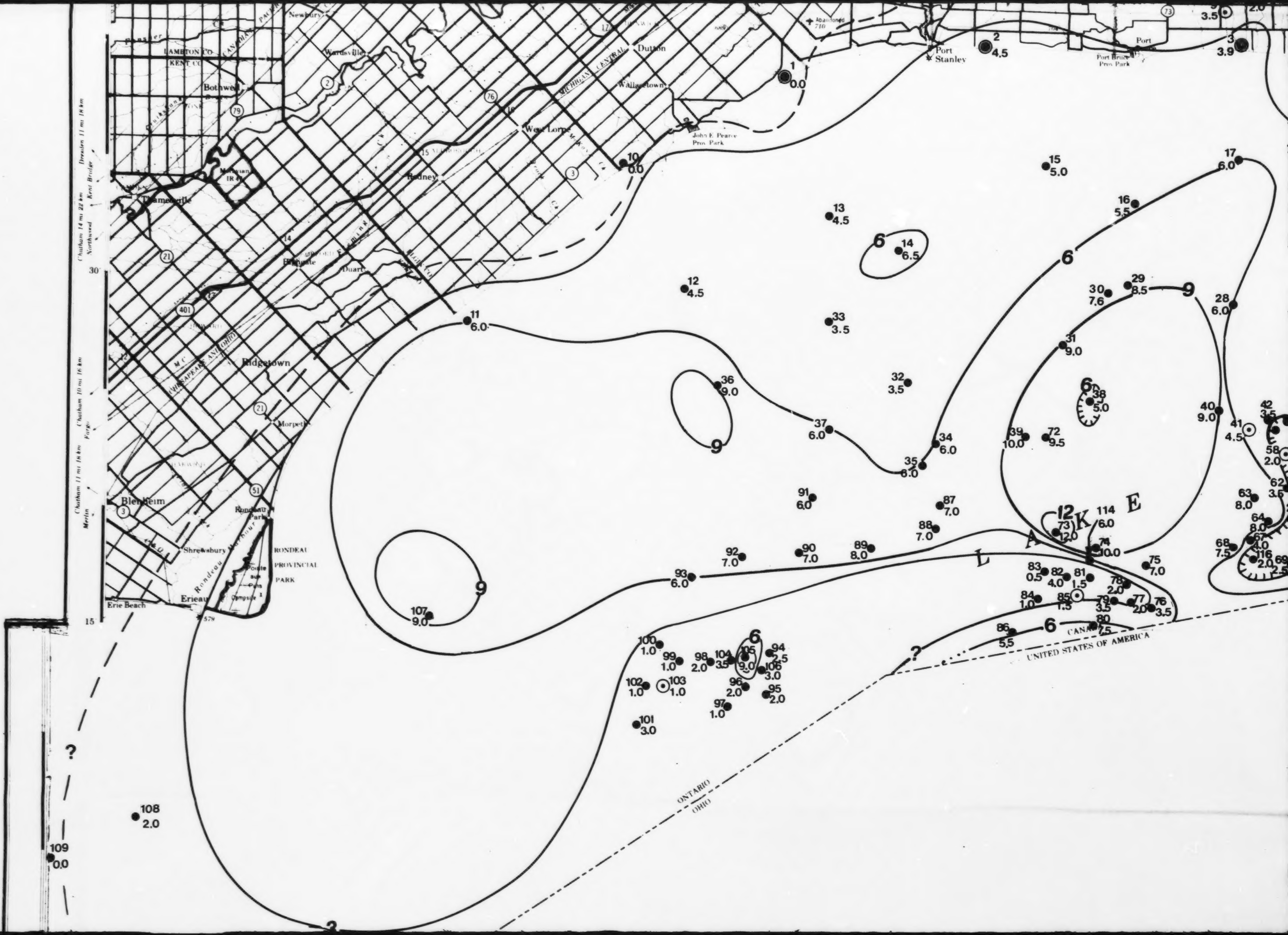
82°00'
45'
30'
15'
81°00'
43°00'
45'
Parkhill 25 mi 40 km
Thedford 17 mi 27 km
Parkhill 13 mi 21 km
Ilderton
Elginfield 15 mi 24 km
Thorndale
Thamesford 12 mi 19 km
Ingersoll
Woodstock 10 mi
Sarnia 20 mi 32 km
Wyoming
Brigden 15 mi 24 km
Dresden 11 mi 18 km
Watford
Kerwood
Strathroy
Komoka
Hyde Park
LONDON
Nilestown
Dorchester
Putnam
Mossley
Mount Brydges
Delaware
Lambeth
Brockley
Harrietsville
Belmont
Glanworth
Lyons
Inwood
Alvinston
Melbourne
Appin
CARADOC IR 42
ONEIDA IR 41
Southwold
Talbotville Royal
Payne Mills
Mapleton
Kingsmill
Springfield
Middlemiss
Lawrence Station
ST THOMAS
Yarmouth Centre
New Sarum
Orwell
Aylmer
Glencoe
Middlemarch
Shedden
Norman
Fingal
Union
Sparta
Newbury
Wardsville
Dutton
Port Stanley
Port Bruce Prov Park
Bothwell
Wallacetown
West Lorne
John E Pearce Prov Park
Rodney
LAMBTON CO
KENT CO
MIDDLESEX CO
ELGIN CO
LONDON
CANADIAN NATIONAL
CANADIAN PACIFIC
MICHIGAN CENTRAL
Thames
Sydenham
Abandoned 710
1 0.0
2 4.5
3 3.9
7 2.0
3.5
10 0.0
15 5.0
17 6.0

CANADA

EDITION 3

40-I


81°00'
45'
30'
15'
80°00'
43°00'
45'
Woodstock 10 mi 16 km
Ingersoll 8 mi 13 km
Brantford 12 mi 19 km
Hamilton 20 mi 32 km
Six Nations IR 40
BRANT CO
Willow Grove
Burford
Dorchester
Nilestown
Pulman
Salford
Mount Elgin
Norwich
Otterville
Springford
Tillsonburg
Ostrander
Culloden
Brownsville
Mossley
Harrietsville
Belmont
Lyons
Springfield
Mapleton
East Kingsmill
Yarmouth Centre
New Sarum
Orwell
Aylmer
Sparta
Port Bruce
Port Bruce Prov Park
Bayham
Straffordville
Eden
Vienna
Port Burwell
Courtland
Delhi
Nixon
Simcoe
Waterford
Teeterville
Windham Centre
La Salette
Vanessa
Wilsonville
Boston
Villa Nova
Townsend Centre
Rockford
Bloomsburg
Hagersville
Jarvis
Nanticoke
Port Dover
Port Ryerse
Vittoria
Walsh
Lynedoch
Silver Hill
Langton
Walsingham
Normandale
Turkey Point
Turkey Point Provincial Park
TURKEY POINT
Deep Hole Point
Port Rowan
Inner Bay
Long Point
Long Point Provincial Park
Ryersons Island
Pottahawk Point
LONG POINT BAY
Clear Creek
OXFORD CO
HALDIMAND-NORFOLK REGIONAL MUNICIPALITY
ELGIN CO
CANADIAN NATIONAL
Big Creek
Otter Creek
Catfish Creek
401
3
6
19
24
59
73
74
2 4.5
3 3.9
4 0.0
5 4.0
6 4.0
7 2.0
8 1.5
9 3.5
15 5.0
17 6.0
19 6.0
111 1.5
112 3.5
113 3.0
3
?


Newbury
Wardsville
LAMBTON CO
KENT CO
Bothwell
Dutton
Wallacetown
MICHIGAN CENTRAL
West Lorne
Rodney
John E. Pearce Prov Park
Abandoned 710
Port Stanley
Port Bruce Prov Park
Port
Thamesville
Moravian IR 47
Highgate
Duart
CHESAPEAKE AND OHIO
Ridgetown
Morpeth
Blenheim
Rondeau Park
Shrewsbury
Rondeau Harbour
RONDEAU PROVINCIAL PARK
Erieau
Erie Beach
Dresden 11 mi 18 km
Kent Bridge
Chatham 14 mi 22 km
Northwood
Chatham 10 mi 16 km
Chatham 11 mi 18 km
Merlin
30
15
2
79
76
3
21
401
51
73
12
15
14
578
L A K E
CANADA
UNITED STATES OF AMERICA
ONTARIO
OHIO
1 0.0
2 4.5
3 3.9
3.5
2.0
10 0.0
11 6.0
12 4.5
13 4.5
14 6.5
15 5.0
16 5.5
17 6.0
28 6.0
29 8.5
30 7.6
31 9.0
32 3.5
33 3.5
34 6.0
35 6.0
36 9.0
37 6.0
38 5.0
39 10.0
40 9.0
41 4.5
42 3.5
58 2.0
62 3.6
63 8.0
64 8.0
67 4.0
68 7.5
116 2.0
69 2.5
72 9.5
73 12.0
114 6.0
74 10.0
75 7.0
76 3.5
77 2.0
78 2.0
79 3.5
80 7.5
81 1.5
82 4.0
83 0.5
84 1.0
85 1.5
86 5.5
87 7.0
88 7.0
89 8.0
90 7.0
91 6.0
92 7.0
93 6.0
94 2.5
95 2.0
96 2.0
97 1.0
98 2.0
99 1.0
100 1.0
101 3.0
102 1.0
103 1.0
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105 9.0
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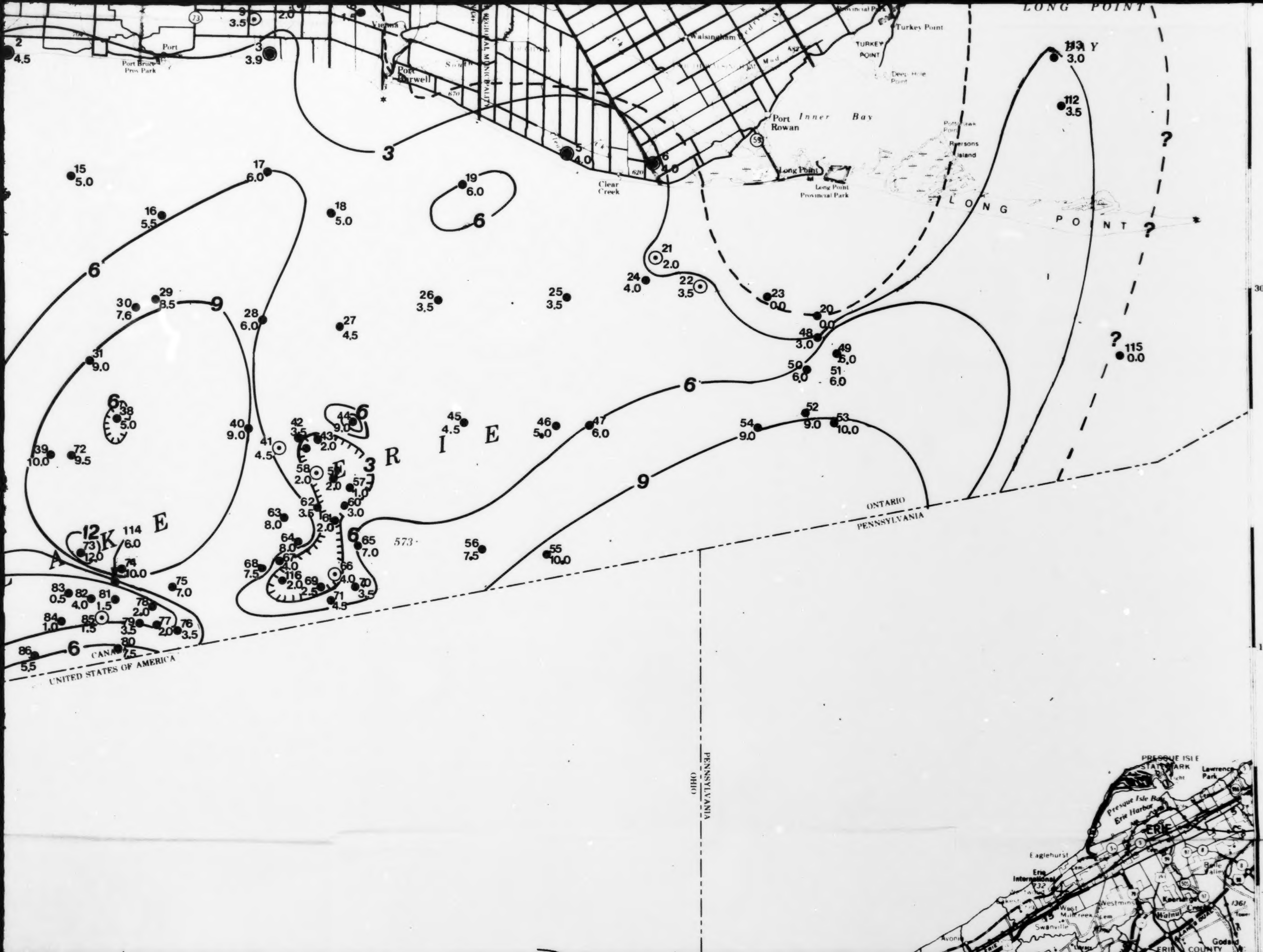
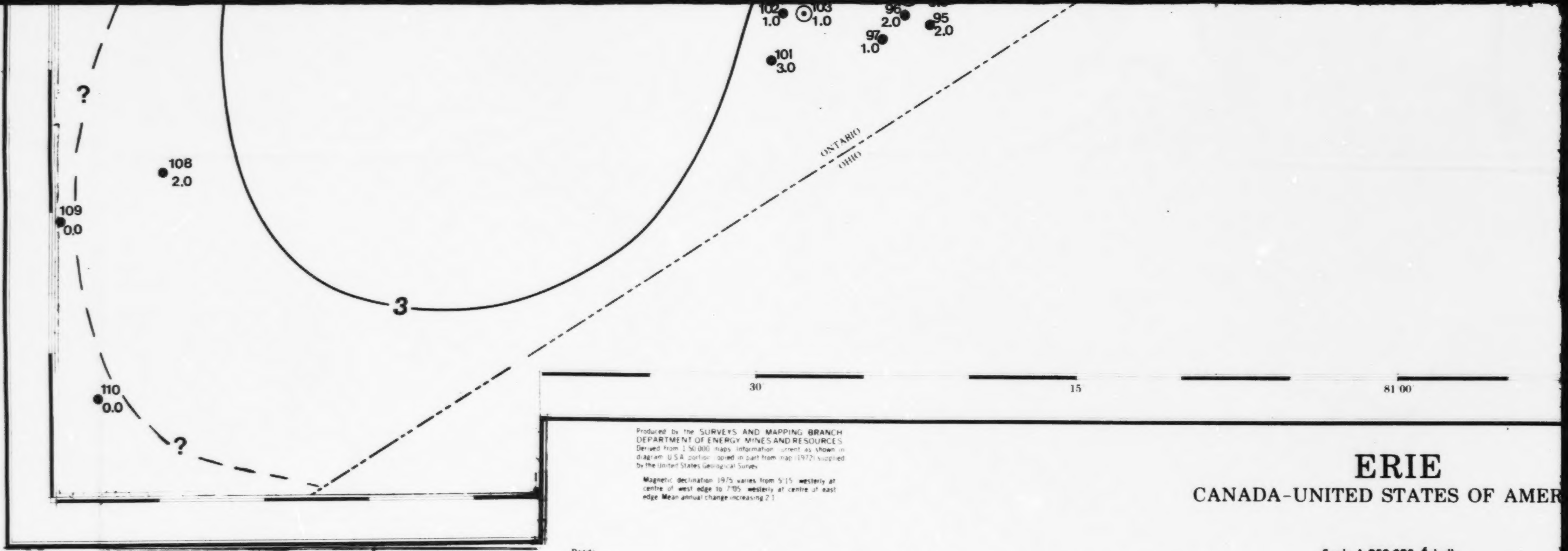
107 9.0
108 2.0
109 0.0
6
9
12
?
3


LONG POINT BAY
Port Bruce Prov Park
Vienna
Port Burwell
Walsingham
Turkey Point
TURKEY POINT
Deep Hole Point
Port Rowan
Inner Bay
Ryersons Island
Long Point
Long Point Provincial Park
Clear Creek
LONG POINT
LAKE ERIE
ONTARIO
PENNSYLVANIA
PENNSYLVANIA
OHIO
CANADA
UNITED STATES OF AMERICA
PRESQUE ISLE STATE PARK
Presque Isle Bay
Erie Harbor
ERIE
Lawrence Park
Eaglehurst
Erie International
West Millcreek
Westminster
Swanville
ERIE COUNTY
Belle Valley
573
30'
15'
3
6
9
12
?



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Magnetic declination 1975 varies from 5°15' westerly at centre of west edge to 7°05' westerly at centre of east edge Mean annual change increasing 2.1'

ERIE

CANADA-UNITED STATES OF AMER

Legend

Isopach Marcellus (metre) —9—

Isopach Marcellus (metre) Formation contact - - 0 - -

O G S cored holes ● 2 I.D number; 4 5 Thickness of Marcellus in metres

Oil & gas exploration holes geophysics & corresponding samples ⊙

Oil & gas exploration holes geophysics or samples ●

Roads

hard surface all weather	dual highway	more than 2 lanes
hard surface all weather	2 lanes	less than 2 lanes
loose or stabilized surface all weather	2 lanes or more	less than 2 lanes
loose surface dry weather		
cart track		
trail, cut line or portage		

FOR COMPLETE REFERENCE SEE REVERSE SIDE

Scale 1:250,000 Échelle

Miles 5 0 5 10

Kilometres 5 0 5 10 15 20

CONTOUR INTERVAL 50 FEET
Elevations in Feet above Mean Sea Level
North American Datum 1927
Transverse Mercator Projection

ÉQUIDISTANCE DES COURBES 50 PIEDS
Élevations en pieds au dessus du niveau moyen d
Système de référence geodesique nord americain
Projection transverse de Mercator

Copies may be obtained from the Canada Map Office Department of Energy Mines and Resources Ottawa or your nearest map dealer

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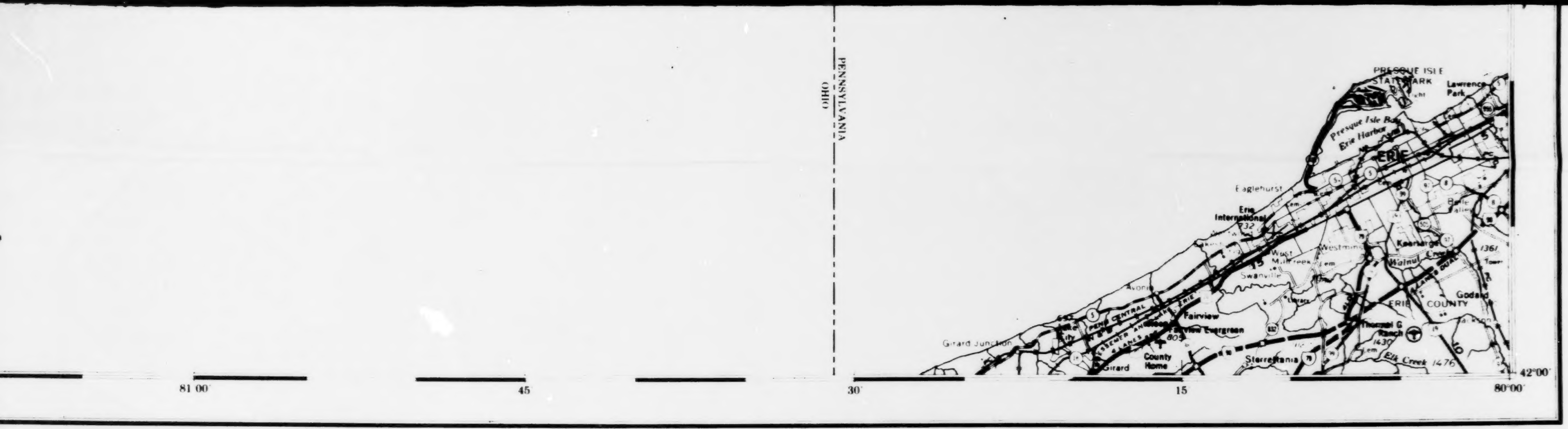
PENNSYLVANIA
OHIO
PRESQUE ISLE STATE PARK
Lawrence Park
Presque Isle Bay
Erie Harbor
ERIE
Eaglehurst
Erie International
West Millcreek
Westminster
Kearsarge
Walnut Creek
Swanville
Avonia
Fairview
Fairview Evergreen
Girard Junction
Girard
County Home
Sterrettania
ERIE COUNTY
Godard
Elk Creek
1476
42°00'
81 00'
45
30'
15
80°00'

ERIE

ANADA-UNITED STATES OF AMERICA

Scale 1:250,000 Échelle

5 10 15 20 Milles

5 10 15 20 25 30 Kilomètres

CONTOUR INTERVAL 50 FEET
Elevations in Feet above Mean Sea Level
North American Datum 1927
Transverse Mercator Projection

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rtment of Energy, Mines and Resources, Ottawa
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ÉQUIDISTANCE DES COURBES 50 PIEDS
Élevations en pieds au dessus du niveau moyen de la mer
Système de référence géodésique nord américain 1927
Projection transverse de Mercator

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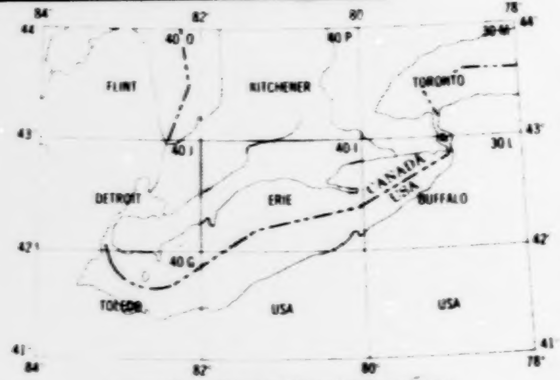
Établie par la DIRECTION DES LEVÉS ET DE LA CARTOGRAPHIE
MINISTÈRE DE L'ÉNERGIE, DES MINES ET DES RESSOURCES
Tirée de cartes 1:50,000. Renseignements à jour tels qu'indiqués au diagramme. Partie américaine reproduite en partie d'après une carte (1972) fournie par le Geological Survey des États Unis

La déclinaison magnétique pour 1975 varie de 5°15' Ouest au centre de la limite Ouest à 7°05' Ouest au centre de la limite Est. Variation moyenne annuelle croissante 2'.

Routes

pavée, toute saison	2 chaussées séparées	plus de 2 voies
pavée, toute saison	2 voies	moins de 2 voies
gravier aggloméré, toute saison	2 voies ou plus	moins de 2 voies
de gravier période sèche		
de terre		
sentier, percée ou portage		

POUR UNE LISTE COMPLÈTE DES SIGNES, VOIR AU VERSO


84°
82°
80
78°
44
43°
42°
41°
40 O
40 P
30 M
FLINT
KITCHENER
TORONTO
40 J
40 I
30 L
DETROIT
ERIE
CANADA
USA
BUFFALO
40 G
TOLEDO
USA
USA

Index to adjoining Maps of the National Topographic System
Tableau d'assemblage du Système national de référence cartographique

ISOPACH OF THE MARCELLUS FORMATION

ERIE
40-I
EDITION 3